INVESTIGATION OF MATERIALS COMBUSTIBILITY, FIRE, AND EXPLOSION SUPPRESSION IN A VARIETY OF ATMOSPHERES

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DYNAMIC SCIENCE
A DIVISION OF MARSHALL INDUSTRIES
MONROVIA, CALIFORNIA

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AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT — PATTERSON AIR FORCE BASE, OHIO

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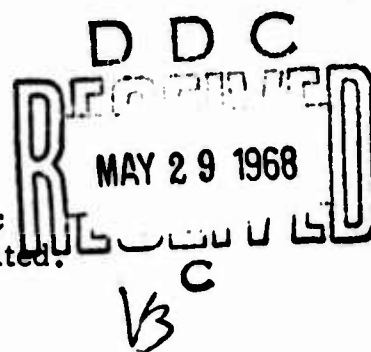Monrovia, California

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FOREWORD

This final report documents the work performed by the Dynamic Science Division of Marshall Industries, Monrovia, California. This effort was sponsored by the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under contract No. AF 33(615)-2257, Project 6075, Task 607504, "Fire and Explosion Characteristics of Aerospace Combustibles." The period covered by this work was from 15 November 1964 to 30 December 1967. All phases of this contract were monitored by B. P. Botteri and R. E. Cretcher, APFL. Dynamic Science personnel contributing to this contract were: H. D. Fisher, M. R. Stevens, F. Kester, M. Gerstein, and J. Ditter. This report was submitted by the authors 29 April 1968.

Publication of this report does not constitute Air Force approval of the report findings or conclusions. It is published only for the exchange and stimulation of ideas.

Arthur V. Churchill, Chief
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Branch
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ABSTRACT

Combustibility studies of materials of construction employed in space flight vehicle cabins have been carried out as a function of various simulated cabin atmospheric environments. The program was conducted under three distinct phases. Phase I efforts were directed at defining the spontaneous ignition temperature, of the individual materials, under dynamic atmospheric conditions for the various atmospheres employed. Phase II centered about the burning characteristics of the respective materials as a function of atmospheric and gravitational environments. These studies also involve the effects of various extinguishants upon the burning characteristics under the influence of several atmospheric environments and gravitational variations. Phase III focused upon the flame spread behavior of the material, under the influence of various atmospheric environments and in the presence of Halon 1301 flame extinguishant. Detailed analyses of the work clearly show the dependency of the combustion behavior of the materials upon the atmospheric environment utilized.

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I. INTRODUCTION

Since November 1964, Dynamic Science has conducted an intense study of the combustion characteristics of materials associated with the construction of aerospace vehicle cabins. This work has been carried out under Contract No. AF 33(615)-2257 sponsored by the Air Force Systems Engineering Group (RTD), Wright-Patterson Air Force Base, Ohio.

There are two specific objectives of this program, namely,

1. To obtain quantitative data with respect to the ignition and combustion properties of the materials, selected for study, under specified flight vehicle cabin environment atmosphere conditions.

2. To study the effect of selected extinguishants for the suppression of fires within the flight vehicle cabin under conditions of terrestrial gravity and extra terrestrial gravity.

To facilitate the planning and execution of the required study, the program was conducted under three phases. Phase I involved the generation of spontaneous ignition temperature data for the selected materials under a range of environmental conditions found in flight vehicle cabin environmental conditions. Phase II of the program centered about the burning characteristics of these materials as a function of gravity under a similar range of flight vehicle cabin conditions including the effects of selected extinguishants. Phase III of the work focused upon the flame spread characteristics of the materials under specific flight vehicle cabin conditions as such and in the presence of specified concentrations of various extinguishants.

This report constitutes the final report of this project. It covers the entire work performed in the period November 1964 to October 1967. The body of the report is composed of three sections, each devoted to the accomplishments achieved under one phase of the project. The final section of the report presents the overall conclusions and recommendations made as a result of this work.

II. EXPERIMENTAL PROGRAM

A. PHASE I. DETERMINATION OF THE SPONTANEOUS IGNITION TEMPERATURE OF SELECTED MATERIALS

1. Introduction

The rapid evolution of spacecraft has rendered it increasingly difficult to design flight vehicle cabins with regard to fire and explosion prevention. Utilization of oxygen enriched, low pressure atmospheres within a sealed cabin makes it imperative to determine the flammable characteristics of the materials employed therein. Of prime importance, in this regard, are the ignition characteristics of materials. Therefore, the first phase of this study is devoted to the determination of the ignition behavior of relevant materials as a function of oxygen concentration and total environmental pressures.

The overall atmospheric environment within the sealed flight cabin is generally subject to a recirculating or recycling process. It was, therefore, felt that the most pertinent ignition data is that obtained under similar conditions, i.e., a dynamic environment. However, under the influence of a dynamic atmospheric environment, the observed minimum ignition temperatures will differ from those generally associated with the ASTM Autogeneous Ignition Temperature designation. Therefore, the minimum ignition temperatures reported here are designated as Spontaneous Ignition Temperatures and are defined as being the lowest temperature of the test specimen at which the material will ignite, under the particular test condition and apparatus employed, without the application of an igniting source, i.e., flame or spark.

In general, the Spontaneous Ignition Temperatures, (S.I.T.) reported here will be higher than those attained by application of the static A.S.T.M. method. This follows from the fact that the sequence of oxidative chemical reactions, which liberate heat and lead to combustion, is disturbed by the removal of heat and chemical intermediates from the vicinity of the test specimen by the circulating flow imposed on the system. Thus, additional heat must be supplied to the test specimen, (raising its temperature) in order

to make up and exceed this loss and thus so permit ignition to take place.

2. Apparatus

Determination of the Spontaneous Ignition Temperature of each test specimen was carried out employing a Combustion Monitor, designed and constructed by Dynamic Science for the Air Force under an earlier contract (AF 33(657)-11075). This unit was specifically designed to investigate the ignition and burning characteristics of combustible materials. Temperature, pressure, and fluid flow are controlled from a console, located immediately in front of two furnace reaction chambers, identified as Furnace No. 1 and Furnace No. 2. Figure 1 illustrates the overall facility. A complete description of this system, together with operating procedures, may be found in Reference 1.

For the present study, Furnace No. 2 was utilized. The furnace reaction chamber is 12 inches in diameter and approximately 18 inches high. Access to the chamber is through a flanged cover sealed with an asbestos gasket which is double-jacketed with 304 stainless steel and tightened with 1/2 inch bolts. A 3-inch diameter viewing port permits observation of the experiment's performance within the chamber. Figure 2 illustrates the No. 2 Furnace Reaction Chamber. Fluid inlets, exhaust ports, electrical leads, and thermocouples enter the chamber from 3 tubes in the bottom of the chamber, as shown. The enclosing furnace is 28 inches square (viewed from the top) and 32 inches high. The solid samples, employed for this work, were placed upon a tray located just above the inlet side of the incoming fluid mixer unit. This stainless steel tray is equipped with a self contained heating unit, allowing the tray temperature to be controlled independently or slaved to that of the main reaction chamber.

In practice, the reaction chamber may be operated under conditions of static atmosphere environments or dynamic atmosphere environments. Both modes of operation may be carried out at constant pressure or variable pressures. The spontaneous ignition temperature determinations reported below were carried out under dynamic atmospheric environments at constant pressure. To accomplish this, the main reaction chamber is equipped with a differential pressure regulator, (a Sterer Valve), manufactured by the Sterer Engineering

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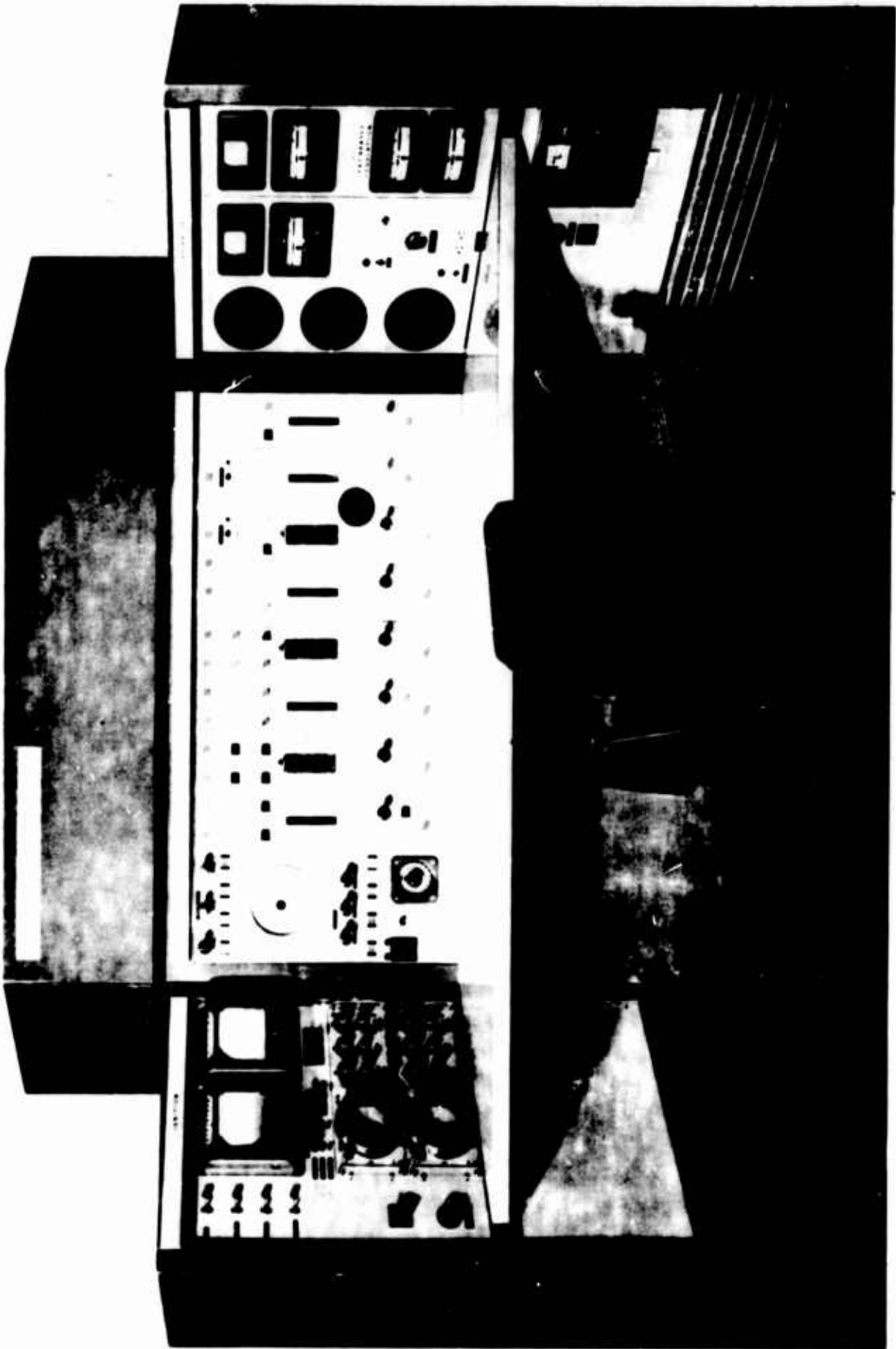
FIGURE 1. Dynamic Science Combustion Monitor Model 164.

Platinum
Ribbon
Igniter

Thermocouples
(Typ.)

1500 Watt
Tray Heater

Heat Exchanger

2" Pipe

1" Pipe

Exhaust

Sheathed
Electrical
Leads (Typ.)

Overhead
Line (Typ.)

Thermocouple
Leads (Typ.)

Conax
Fittings

Fluid Inlet Lines

18°

12"

View Port
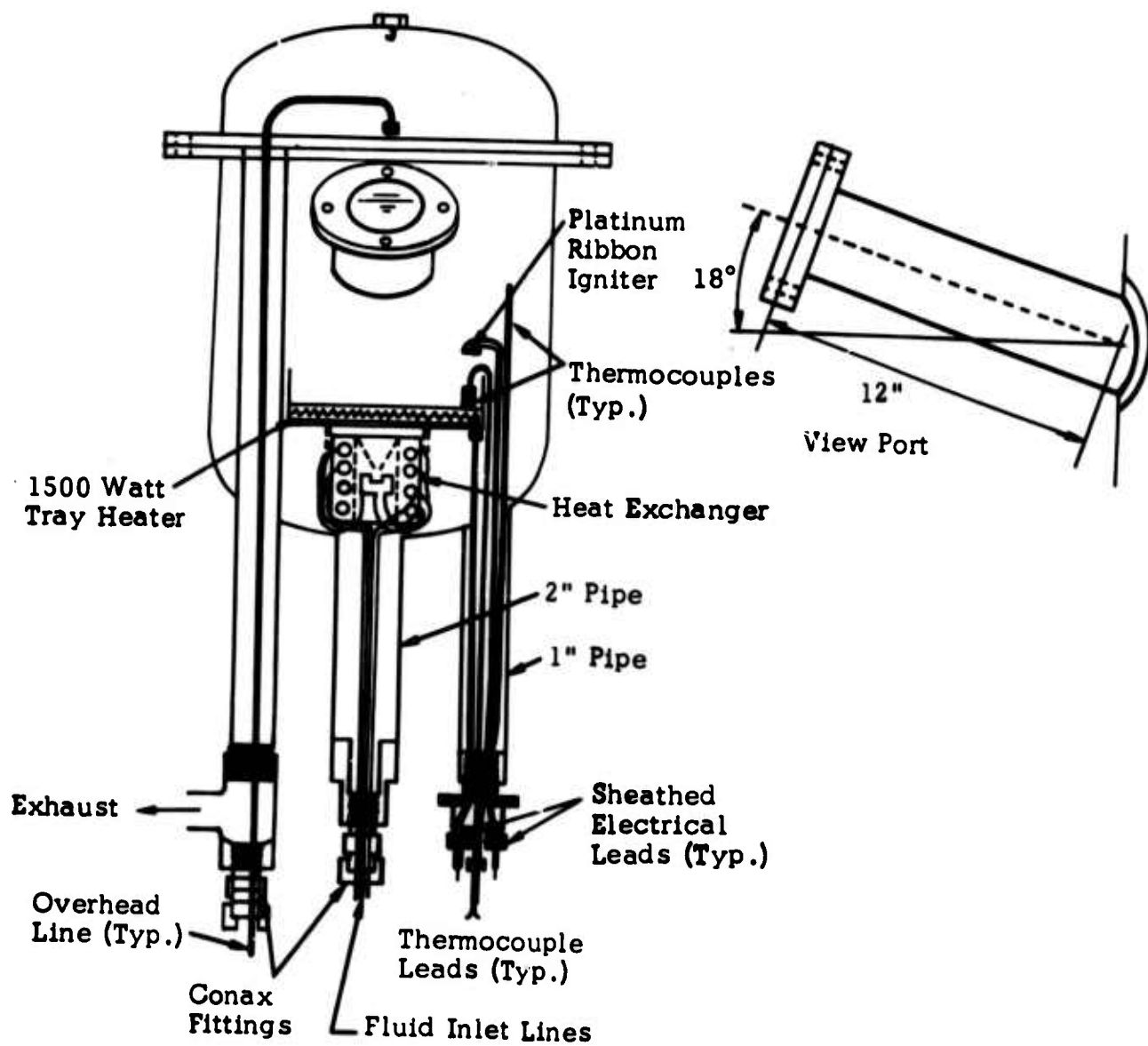
FIGURE 2. No. 2 Furnace Chamber.

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Company of Los Angeles.

Additional equipment employed for these tests were a Vacuum Manifold System, a Gas Chromatograph, and a Beckman Oxygen Analyzer. The vacuum manifold system was connected to the No. 2 Furnace Reaction Chamber. This system was employed to obtain samples of preignition and post-ignition atmospheres from the reaction chamber. Gaseous samples, so taken, are analyze ' by the Gas Chromatograph. The chromatograph utilized was a Micro Tech 2500R, and was directly connected to the vacuum manifold system. It was fitted with molecular sieve and silica gel columns, both 10 feet long by 1/4 inch in diameter. The columns were operated at $150^{\circ}C$ with helium carrier gas at a flow rate of 60 cc/min. The Beckman Oxygen Analyzer was employed to monitor the oxygen content of the incoming environmental gases.

Suitable thermocouples were used to control and/or indicate temperature at critical areas within the reaction chamber. One such unit monitored the overall environmental temperature. A second unit monitored the tray temperature, while a third unit monitored the test specimen temperature. Total pressure within the chamber was continuously monitored by means of a Statham Pressure Transducer of 0-30 psia range.

3. Procedure

The test sample is placed upon the surface of the tray heater, located in the No. 2 Furnace Reaction Chamber. The specimen thermocouple is placed in contact with the upper (exposed) surface of the sample. At this point, the reaction chamber is sealed, evacuated, and leak checked. With the chamber isolated from the vacuum, the desired atmosphere is introduced and the chamber pressure is then set by adjusting the reference pressure on the Sterer Value to the desired operating level.

When the operating pressure level is reached, the gas flow rate is adjusted such that the chamber atmosphere is changed at a constant rate, independent of the operating pressure. The S.T.P. flow rates used at various chamber pressures are shown in Table I.

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The furnace heater is now activated and the power level adjusted as required. The tray heater is then activated and its power level adjusted. Recorders monitoring chamber pressure and temperatures are activated. The test run has started.

TABLE I

GAS FLOW RATES THROUGH REACTION CHAMBER AT STP AT VARIOUS CHAMBER PRESSURES

Operating Pressure, mm Hg.	Flow Rate, Liters/Minute
760	4
569	3.2
362	1.87
259	1.33

4. Experimental Results

Eleven materials were selected for study under this phase of the program. They were selected on the basis that each represented a basic material present within the flight vehicle cabin. The Spontaneous Ignition Temperature (SIT) of each material was determined primarily as a function of oxygen concentration and total environmental pressures. Eight were subjected to intensive study, three were spot checked only. Data for only three of the materials have been previously reported (2).

(a) Polyethylene

The polyethylene S.I.T. study was the first to be carried out. Table II presents all the data obtained in the course of the polyethylene experimental test program. In these initial experiments an effort was made to ascertain the relative importance of such variables as sample size, heating rate, flow rate, pressure, and oxygen concentration upon observed S.I.T. values. This data had been reported in Summary Report No. SN-6401(2). As presented in Table II, the data have been rearranged for purposes of clarity and evaluation. Several variables previously considered (2) have been omitted here since

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TABLE II. SPONTANEOUS IGNITION TEMPERATURE OF POLYETHYLENE

Run No.	Atm. Composition (%) O2	N2	He	Pressure (mm Hg)	Flow Rate l/Min.	Size (Inches)	Heating Rate °C/min	S.I.T. °C	Remarks
118	100	-	-	760	0	1x1x3/8	6	248	Increase of flow rate
119	100	-	-	760	0	4x4x3/8	5.5	250	increases S.I.T.
104	100	-	-	760	2.3	1x1x3/8	3	250	Compare runs 104 and
115	100	-	-	760	4.2	1x1x3/8	7.5	223	120, 131.
120	100	-	-	760	6.5	1x1x3/8	10.0	264	Sample surface area
131	100	-	-	760	0	1x1x3/8	3.5	230	does not affect S.I.T.
106	50	50	-	760	4.8	1x1x3/8	3.5	262	Compare runs 118 and
112	75	-	25	760	4.1	1x1x3/8	–	242	119.
114	25	-	75	760	4.0	1x1x3/8	7.5	No Ignition	
125	100	-	-	569	0	3x3x3/8	9.8	300	S.I.T. function of
103	100	-	-	569	1.9	1x1x3/8	2.0	250	oxygen concentration.
113	75	25	-	569	4.4	1x1x3/8	12.0	244	Compare runs 113, 108
108	50	50	-	569	5.3	1x1x3/8	–	282	and 110.
110	20	80	-	569	5.2	1x1x3/8	–	No Ignition	
111	20	80	-	569	5.6	1x1x3/8	–		
102	100	-	-	362	1.4	1x1x3/8	5.4	300	Run 102 appears
116	75	25	-	362	4.2	1x1x3/8	14.0	291	out of line. Compare
107	50	50	-	362	3.0	1x1x3/8	–	No Ignition	102 with 125.
121	100	-	-	259	0	1x1x3/8	10	319	Within narrow limits
128A	100	-	-	259	1.4	1x1x3/8	4	310	sample thickness will
129	100	-	-	259	1.4	1x1x3/8	4	No Ignition	affect S.I.T.
130	100	-	-	259	1.4	1x1x1/8	6	311	Runs 128A, 101 and
101	100	-	-	259	1.1	1x1x3/8	4.4	305	121 definitely discount
105	100	-	-	259	2.9	1x1x3/8	4	302	affect of flow on S.I.T. as a parameter in these experiments.

they have no bearing on the observed S.I.T. values. Examination of the tabulated data indicates that:

1. Within the test limits, variation of sample surface area does not affect the observed S.I.T. values. This may be seen by comparing runs 118 and 119.

2. Within the test limits, variation of sample thickness will affect observed S.I.T. values. This is seen by comparing runs 130 and 129.

3. The effect of the flow rate upon the observed S.I.T. values is not sharply defined. Based upon the tests conducted in 100% oxygen at 760 mm Hg, when the flow rate is fast, the observed S.I.T. value increases with respect to the static S.I.T. value. When it is slow, the observed S.I.T. value decreases from that noted for static ambient atmospheres. The former observation is in line with that anticipated, as stated at the start of this section. The latter observation must result from the fact that at relatively low flows, the increased oxygen supply at the vicinity of the heated specimen promotes the chemical reactions leading to ignition without noticeably changing the concentration of reaction intermediates or removing heat from the vicinity of the test specimen. In other words, the low flow induces better mixing at the site of the chemical activity without undue loss of heat or reactants from this site.

4. Variation of the heating rate has, at most, a minimal affect on the observed S.I.T. values.

5. Substitution of helium for nitrogen, as the diluent, appears to lower the observed S.I.T. value. This, however, is not clearly defined by this data. Additional tests are required to amplify the effect of helium as a diluent.

6. Decreasing the oxygen concentration increases the S.I.T. values observed.

The Spontaneous Ignition Temperature of Polyethylene as a function of oxygen concentration is given by Figure 3. Figure 4 presents the variation of the S.I.T. values for polyethylene as a function of the total ambient pressure when the percent oxygen of the ambient atmosphere is held constant. Both figures clearly demonstrate the dependency of the observed S.I.T. values upon the oxygen concentration.

In conjunction with the experimental determination of the S.I.T. for polyethylene, consideration was given to the analysis of the gaseous atmosphere existing within the reaction chamber prior to and following ignition of the test sample. It is known that the initial step of the combustion process of solid materials is the pyrolytic decomposition of the material. Pyrolysis of polyethylene in a vacuum, leads to copious amounts of unsaturated and saturated hydrocarbons. The same process in an oxygen containing atmosphere would lead to oxygenated hydrocarbons, as aldehydes, alcohols, etc., in addition to CO and CO_2 prior to the point of ignition. When ignition occurs, the relative amounts of CO and CO_2 (and water) would increase at the expense of the CHO type compounds. However, they would still be present to some extent. Analysis of the atmosphere, containing these materials, is beyond the scope of the present study. Therefore, it was decided to limit the atmospheric analyses to the "permanent" gases, i.e., CO_2, CO, and O_2, before, at, and after the ignition of the specimen. By considering the ratio of these gases, one is able to follow the ignition process by noting the variation of this ratio. For several of the materials such techniques were employed. In the present case, only a qualitative evaluation of the test chamber atmosphere was made. Carbon monoxide and carbon dioxide were present during the combustion process. No "hydrocarbons" were detected. This was due to the analytical procedure employed rather than due to their complete absence.

(b) Polyvinylchloride

Determination of the Spontaneous Ignition Temperature of Polyvinylchloride was made utilizing a more formalized approach. The tests conducted with polyethylene, Part (a) of this section, have shown that certain variables have little or no significance upon the observed S.I.T. values. Accordingly, these

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NO IGNITION

A. 259 mm Hg PRESSURE
B. 569 mm Hg PRESSURE
C. 760mm Hg PRESSURE
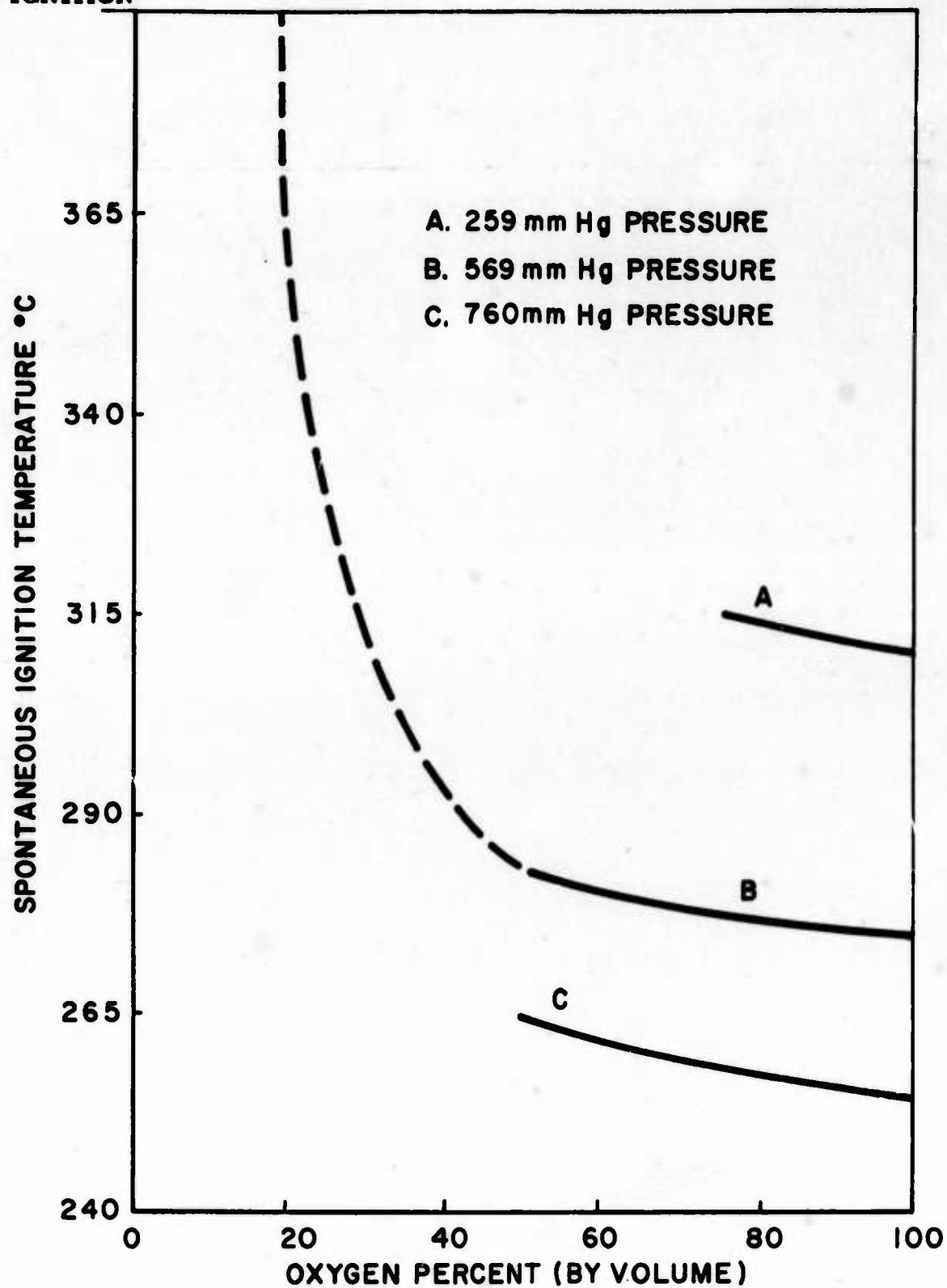
FIGURE 3. Spontaneous Ignition of Polyethylene as a Function
of Oxygen Concentration at Selected Ambient Atmospheric
Pressures (N₂ Diluent in All Cases).
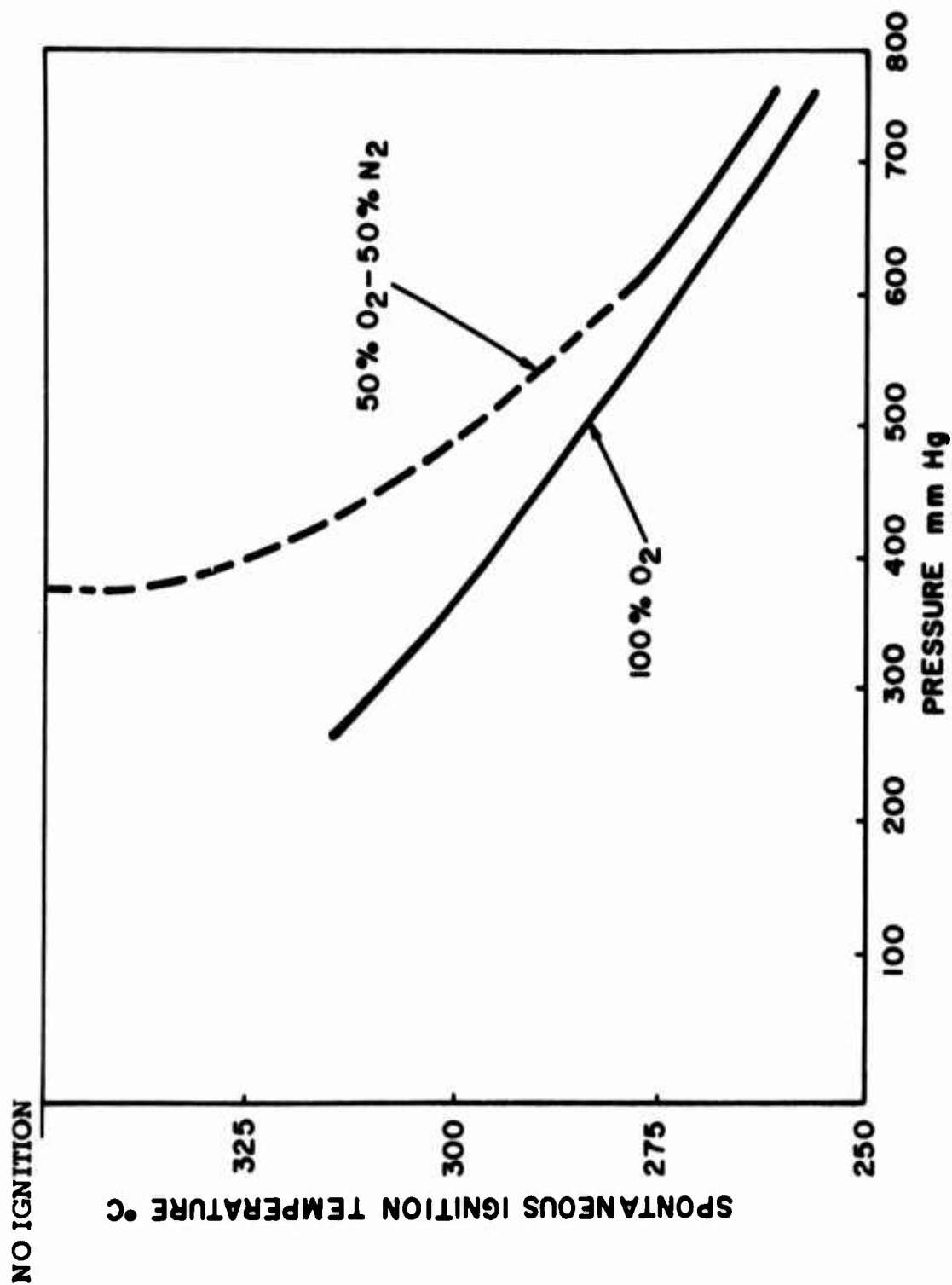
FIGURE 4. Spontaneous Ignition Temperature of Polyethylene as a Function of Total Pressure of Ambient Atmospheres Containing a Constant Percentage of Oxygen.

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variables, notably flow rate, heating rate, and sample size have now been standardized. The flow rates employed throughout the remainder of this phase of the work are those given in Table I; sample size was held constant, as was the heating rate (as far as possible).

Data for the observed S.I.T. values of polyvinylchloride are presented in Table III. The data have been arranged in a different manner from that previously reported (2), for purposes of clarity and evaluation. Figure 5 presents the S.I.T. data as a function of the oxygen concentration at various total ambient atmospheric pressures. Figure 6 presents the S.I.T. data as a function of the total ambient atmospheric pressure for constant percentages of oxygen in the atmosphere.

For these tests four one inch squares, each 1/16 inches thick, of polyvinylchloride were "stacked" and placed onto the tray heater. No attempt was made to standardize, or control, the degree of compaction of each stack. During each test run, an increase in sample volume resulted when heat was applied to the test specimen. Visual "swelling" of the material took place at approximately $280^{\circ}C$, accompanied by the formation of a carbonaceous, honeycomb mass. Upon ignition, the entire "stack" was surrounded by a mantle of fire. At the occurrence of "swelling," the temperature of the surface rose sharply. It is recognized that the degree of compactness of the stack has a direct bearing upon the experimental results. It dictates the amount of "swelling" and subsequent carbonaceous formation, which in turn controls the degree of surface chemical activity between the sample surface and oxygen or between the pyrolyzed product and oxygen at the surface. Consequently, this activity influences the ignition characteristics of the "stack" and therefore the observed S.I.T. values. In most cases, the S.I.T. values are probably low in magnitude.

Nevertheless, the data clearly indicates that the Spontaneous Ignition Temperature of polyvinylchloride is a direct function of the oxygen concentration. Further, the substitution of helium for nitrogen, as the atmospheric diluent, produces a minimal effect, at most, upon the observed S.I.T. values.

TABLE III. SPONTANEOUS IGNITION TEMPERATURE OF POLYVINYLCHLORIDE
DIMENSIONS: 4 PIECES, EACH 1 x 1 x 1/16

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (l/min)	Heating Rate °C/min	S.I.T. °C	Remarks
	O_2	N_2	He					
201	100	--	--	760	4	5	480	
204	100	--	--	760	4	3.5	452	
205	100	--	--	760	4	3.5	462	
206	100	--	--	569	3.2	4	462	
206A	100	--	--	569	3.2	5	452	Sample in O_2 Atm. 30 days
209	100	--	--	569	5.2	7.5	502	Inc. of Flowrate, Inc. S.I.T.
220	100	--	--	569	3.2	6.5	510	
212	100	--	--	362	1.9	8	539	
215	100	--	--	259	1.3	5	552	
202	60	40	--	760	4	5	537	
207	60	40	--	569	3.2	5	562	
213	60	40	--	362	1.9	5	535	Value low.
218	60	40	--	362	1.9	5	572	
216	60	40	--	259	1.3	5	600	
203	20	80	--	760	4	5	No ignition	Runs below 760 mmHg of this series were not needed.
203A	20	80	--	760	4	5	"	
208	20	80	--	569	3.2	5	"	
208A	20	80	--	569	5.2	5	"	
211	20	80	--	569	5.2	5	"	
217	20	80	--	259	1.3	5	"	
219	20	80	--	259	1.3	5	"	
214	20	80	--	362	1.9	5	"	
210	60	--	40	569	5.2	5	568	Helium, as diluent, does not have great effect upon S.I.T.

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FIGURE 5. Spontaneous Ignition Temperature--Polyvinylchloride as a Function of Oxygen Concentration at Various Total Ambient Atmospheric Pressures.

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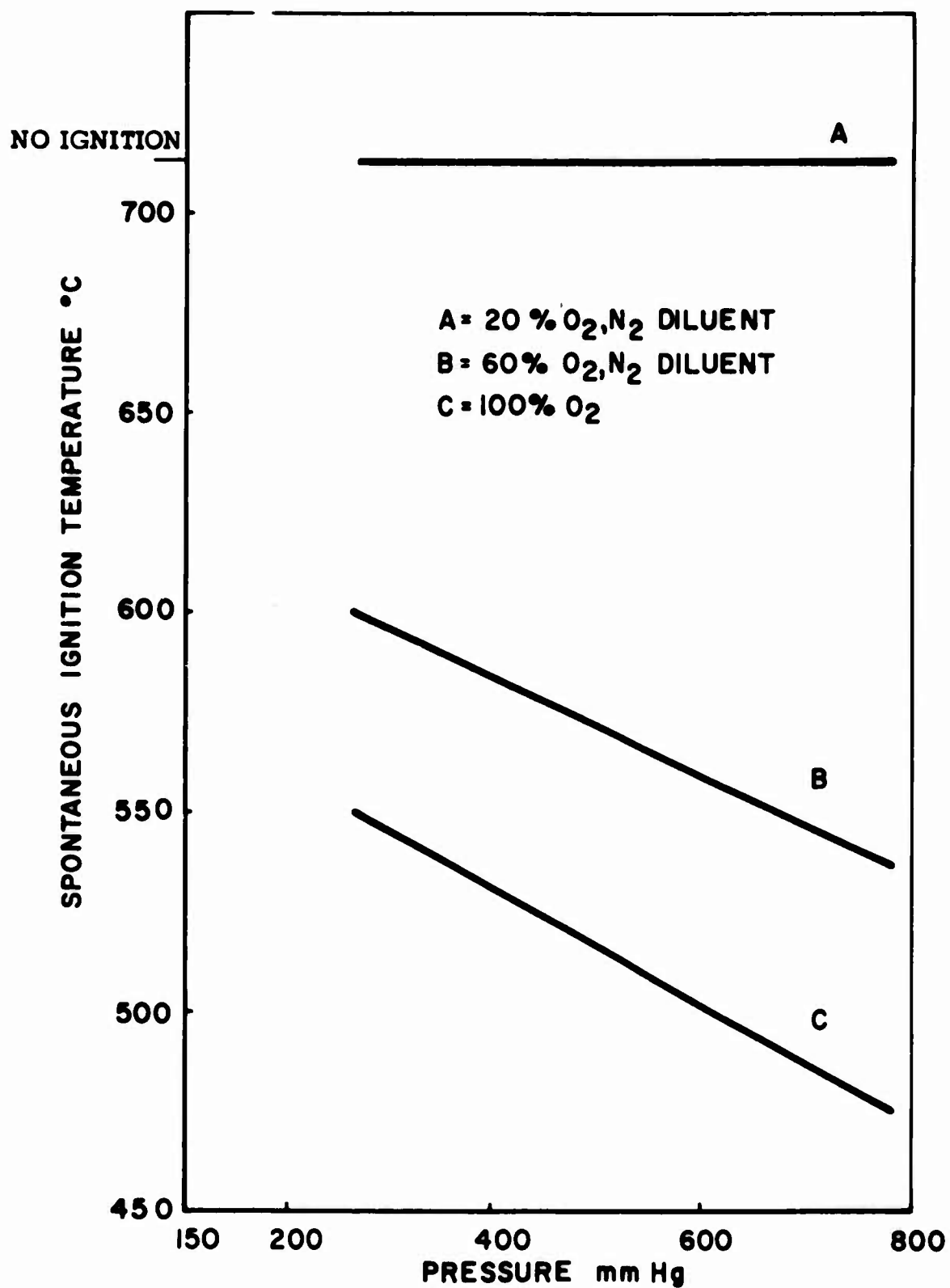
FIGURE 6. Spontaneous Ignition Temperature of Polyvinylchloride as a Function of Pressure at Various Oxygen-Nitrogen Concentrations.

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When these tests were conducted, the Micro-Tech chromatograph was inoperable. Consequently, no analysis of the chamber gases were able to be performed.

(c) Silicone Rubber

Spontaneous ignition test data for G-2078 silicone rubber are given in Table IV. For this test series, the test specimen consisted of a "stack" of two one inch squares of material, each 1/8 inch thick. Consequently, the comments made above concerning the degree of compaction and its effect upon observed S.I.T. values apply here also.

In the course of each test run, an oil evolved from the test specimen at approximately 200°C. The volatile silicone oil first condensed upon the cooler portions of the reaction chamber and then underwent apparent oxidation as the test chamber temperature increased. This secondary reaction resulted in the formation of a heavy deposit of white film on the viewing window of the reaction chamber, together with a suspension of fine silica within the chamber volume. When the test specimen temperature reached approximately 400°C, the specimen volume began to swell, reaching a volume eight times as large as its initial volume. These phenomena occurred prior to ignition of the specimen.

Examination of the data in Table IV indicates that the ignition behavior of this material is considerably different from that encountered with previous (and subsequent) test materials reported here. There appears to be no clearly defined dependence of the observed S.I.T. values upon the oxygen concentration. The data overlap to a large extent. Samples, pre-soaked in 100% oxygen for 30 days prior to testing show no distinct S.I.T. values which differ from test specimens not treated as such.

To what extent this ignition pattern is due to the appearance, and subsequent reactivity, of the volatile oil is not known. Such activity indicates sample decomposition. The degree of compaction will affect the extent of the sample decomposition and consequently, the extent of oil evolution from the material, as well as the degree to which the sample will expand. The overlap of the data results in part from the fact that the compaction, hence pyrolysis, of the sample was not reproducible.

TABLE IV. SPONTANEOUS IGNITION TEMPERATURE OF SILICONE RUBBER
DIMENSIONS: 2 PIECES, EACH 1 x 1 x 1/8 INCHES

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (l/min)	Heating Rate °C/min	S.I.T. °C	Remarks
	O_2	N_2	He					
301A	100	--	--	760	4	3.5	496	
301B	100	--	--	760	4	3.3	498	
310	100	--	--	760	4	4	488	
311	100	--	--	760	4	4	492	Sample aged in O_2 for 30 days
318	100	--	--	760	4	--	485	
302	100	--	--	569	3.2	5	498	
302A	100	--	--	569	3.2	3.3	495	
313	100	--	--	569	3.2	4	505	
303	100	--	--	362	1.9	3.3	No Ignition	Faulty run
303A	100	--	--	362	1.9	3.3	510	
303B	100	--	--	362	1.9	3.5	500	
304	100	--	--	259	1.3	3	500	
305	60	40	--	760	4	3.3	495	
306	60	40	--	569	3.2	4	498	
307	60	40	--	362	1.9	2.5	498	
308	60	40	--	259	1.3	3.3	498	
308A	60	40	--	259	1.3	3.4	505	
309	20	80	--	760	4	3.3	510	
319	20	80	--	760	4	--	515	
312	20	80	--	569	3.2	3.5	512	
315	20	80	--	569	3.2	--	528	
316	20	80	--	362	1.9	--	No Ignition	
317	20	80	--	259	1.3	--	No Ignition	
320	20	80	--	569	1.9	--	502	
314	60	--	40	569	3.2	4.3	508	

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However, if the above cited S.I.T. values for a particular ambient atmospheric pressure are averaged, the S.I.T. data are shown to exhibit a dependency upon the oxygen concentration as shown by Figure 7. In drawing the 569 mm Hg curve, the data point for 60% oxygen was omitted. In light of the above discussion these curves should be considered qualitatively only.

Analyses of the ambient atmosphere within the test chamber was carried out for each experimental run cited above. As indicated earlier, the analyses was restricted to oxygen, carbon monoxide, and carbon dioxide. Table V presents the results of these analyses. The data are given as a function of sample temperature and time. The partial pressure of oxygen is shown to decrease appreciably just prior to ignition. At the same time, the partial pressure of carbon monoxide maximizes. With the appearance of the flame the concentration of CO decreases while that of CO_2 increases rapidly. The oxygen concentration continues to decrease in this period of time.

(d) Hydraulic Fluid

The Spontaneous Ignition Temperature data for MIL-H-8446B Hydraulic Fluid are given in Table VI. Testing of this liquid polyester necessitated a change in the operating procedure previously established. The tests were performed by introducing the preselected atmosphere into the reaction chamber, adjusting the pressure to the desired level followed by energizing the furnace and tray heaters. The hydraulic fluid was then introduced directly onto the surface of the tray heater by means of a flow control solenoid valve injection system. A 1/2 cc volume of fluid was injected onto the tray each time. The delivery of the system was calibrated in terms of the time required for the valve to be in its open position.

Since the fluid is in direct contact with the tray heater surface in the form of a film of varying depth and area, the tray heater temperature at the onset of ignition is taken as the S.I.T. for a particular test. Repeated injections of the fluid, to the tray, were made at $10^{\circ}C$ intervals of tray heater temperature until the S.I.T. was attained.

Figure 8 illustrates the dependence of the observed S.I.T. values upon the oxygen concentrations at various total ambient atmospheric pressures.
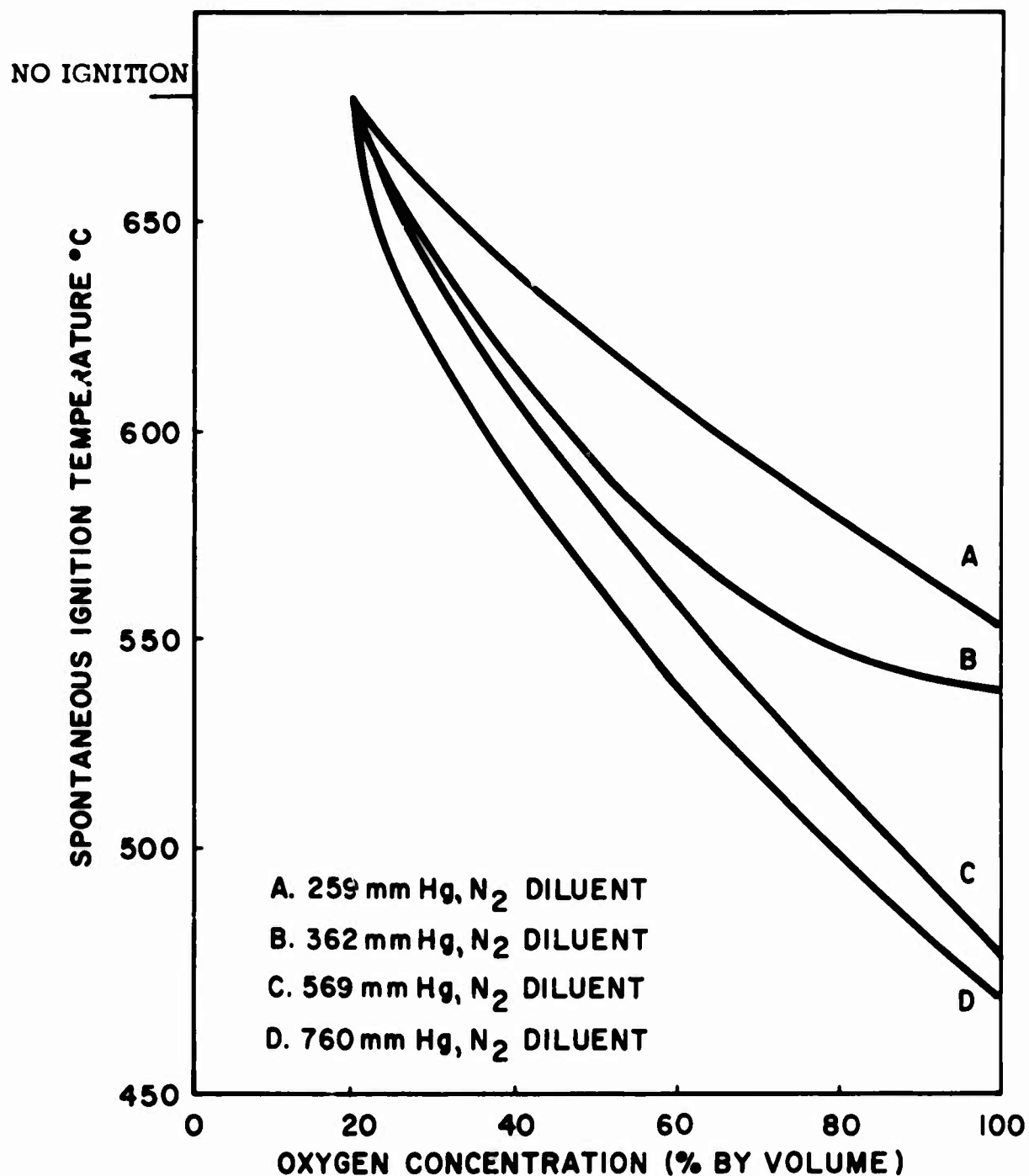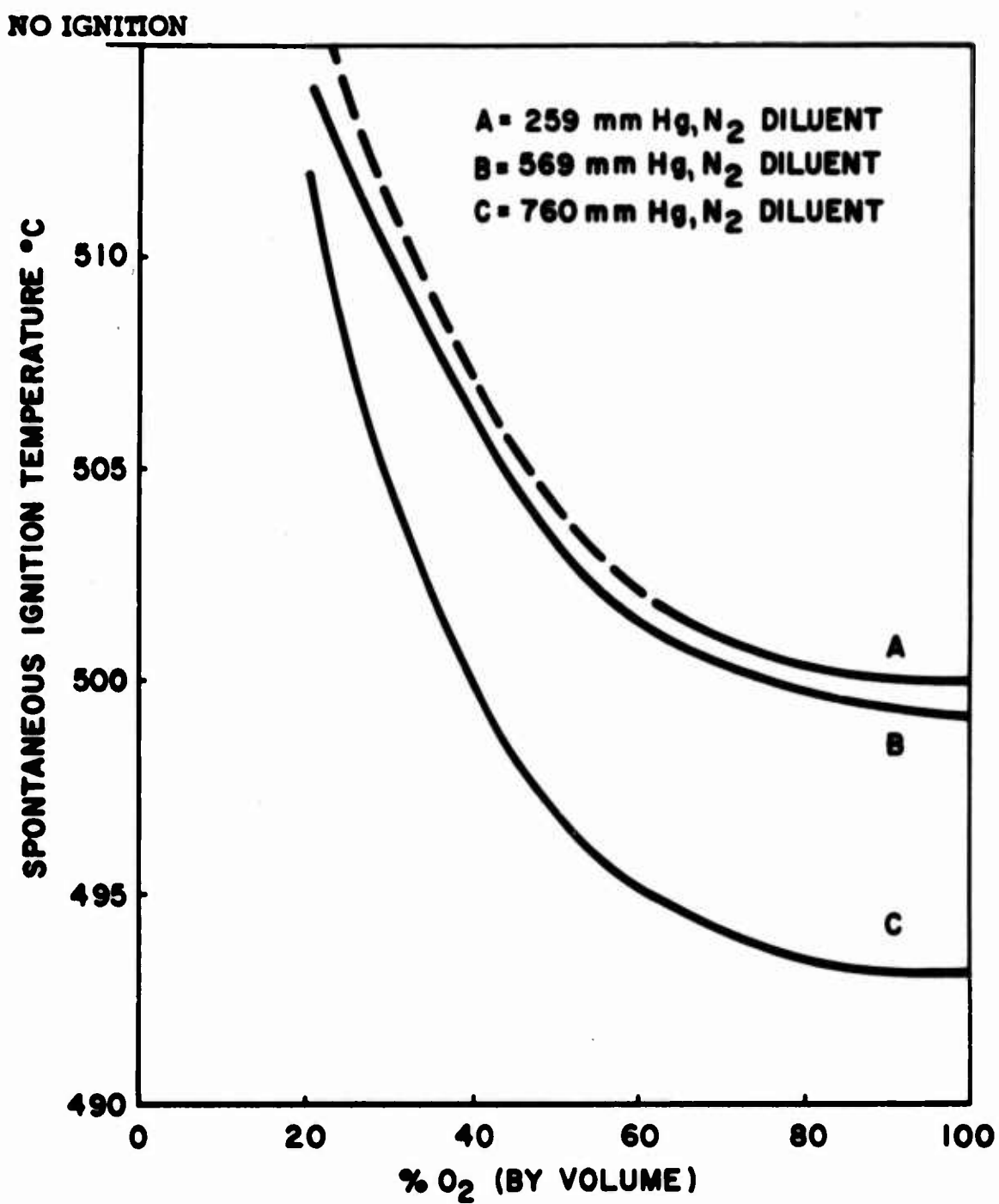
FIGURE 7. Spontaneous Ignition Temperature of Silicone Rubber as a Function of Oxygen Concentration at Various Total Atmospheric Pressures.

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## TABLE V. ATMOSPHERE COMPOSITION DURING IGNITION OF SILICONE RUBBER AS FUNCTION OF TIME

Run No.	Atm Composition (%) O_2	N_2	He	Pressure (mm Hg)	Time (Min)	Sample Temp. °C	Atmosphere Composition (mm Hg) O_2	CO	CO_2	Remarks
302A	100	-	-	569	24	215	569	0	0	
					31	280	672.1	7.55	0	
					41	350	560.2	-	-	
					51	400	672.1	1.53	-	
					59	440	553.3	9.63	2.15	
					65	465	511.3	12.76	3.94	Slow ignition - orange
					68	475	489.3	13.27	-	Slight glow
					73.30	-	424.3	6.54	22.3	
					74.0	700	-	-	-	
					75	790	392.3	3.44	4.02	
303	100	-	-	362	30	345	362	-	-	
					35	380	411.6	0.71	1.85	
					40	410	308.4	6.13	3.33	
					45	440	355.9	9.55	8.99	
					50	460	350.2	10.9	13.6	
					52	472	281.4	6.28	11.1	
					56	493	182.9	3.27	3.10	
					60	515	163.2	2.30	2.68	
					63	520	153.7	1.75	2.61	
					67	-	-	-	-	
305	60	40	-	760	40	338	454.0	-	-	
					55	410	462.3	3.51	1.16	
					61	438	430.6	9.88	2.21	
					70	470	429.2	11.9	7.48	
					75	488	421.7	12.9	13.7	
					77.20	495	424.0	10.4	17.6	
					79	770	421.4	5.41	-	Ignition - yellow flame

TABLE V. (CONTINUED)

Run No.	Atm Composition (%) O₂	N₂	He	Pressure (mm Hg)	Time (Min)	Sample Temp. °C	Atmosphere Composition (mm Hg) O₂	CO	CO₂	Remarks
306	60	40	–	569	45	368	359	–	–	
					55	415	368.9	1.92	–	
					65	455	366.5	7.59	2.01	Ignition – orange flame
					74	490	304.7	8.15	7.99	
					76.10	498	355.9	5.92	8.02	
					78	705	–	–	–	
307	60	40	–	362	51	375	216.53	–	0.47	
					60	420	227.9	2.07	–	
					66	440	192.2	6.53	2.24	
					70	460	214.7	6.71	3.54	
					77	485	174.6	5.88	9.69	Ignition – orange flame
					82.10	498	195.8	2.22	28.54	Flame dying
					83	650	–	–	–	No flame – red glow
					84	650	–	–	–	Appears out
					86	615	189.2	2.93	24.2	
308A	60	40	–	259	30	245	155	–	–	
					50	365	175.4	–	–	
					65	428	163.7	3.39	1.75	Ignition – orange flame
					75	462	192.7	6.36	3.30	Flame died then flared
					83	490	156.3	4.78	8.21	Glow
					89.10	508	149.6	2.81	1.81	Out
					91	–	–	–	–	
					92	–	–	–	–	
					94	–	–	–	–	

TABLE V. (CONTINUED)

Run No.	Atm Composition (%) O₂	N₂	He	Pressure (mm Hg)	Time (Min)	Sample Temp. °C	Atmosphere Composition (mm Hg) O₂	CO	CO₂	Remarks
309	20	80	-	760	31	280	152	-	-	
					51	400	122.3	0.27	0.16	
					60	440	120.5	4.00	0.71	
					72	490	139.1	6.73	5.32	
					77.15	510	118.2	5.56	12.45	
					82	585	115.6	1.63	1.47	Ignition
310	100	-	-	760	30	262	-	-	-	30 day exposure to 100% O₂
					40	335	-	-	-	
					45	368	760	0	0	
					55	410	-	-	-	
					71	468	740	7.1	11.3	
					75	480	-	-	-	
					77.5	488	715	35.3	9.6	Ignition
					80	720	688	65.8	5.5	
					81	610	695	59.3	5.6	
					90	490	-	-	-	
311	100	-	-	760	30	325	-	-	-	30 day exposure to 100% O₂
					35	360	760	0	0	
					45	415	-	-	-	
					60	478	745	6.5	8.1	
					64.25	492	730	20.8	9.2	
					65.5	820	680	75.4	3.1	Ignition
					66.8	650	699	55.6	5.2	
					68	630	-	-	-	

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TABLE V. (CONTINUED)

Run No.	Atm Composition (%) O₂	N₂	He	Pressure (mm Hg)	Time (Min)	Sample Temp. °C	Atmosphere Composition (mm Hg) O₂	CO	CO₂	Remarks
312	20	80	-	569	30	225	-	-	-	
					45	340	119	0	0	
					56	390	-	-	-	
					69	440	-	-	-	
					80	480	108	3.8	6.9	
					89	510	103	9.5	6.9	
					91.25	512	97	14.3	7.3	Ignition
					93	525	-	-	-	
					95	560	97	17.2	4.4	Flash
					97	530	94	14.8	9.8	
313	100	-	-	569	30	270	-	-	-	
					46	362	569	0	0	
					60	425	-	-	-	
					76	480	555	6.6	7.1	Ignition
					83	505	539	22.3	6.9	
					84	835	499	66.6	2.6	
					85	710	-	-	-	Flame out
					86	635	534	30.6	3.5	
314	60	-	40	569	30	328	-	-	-	
					39	380	340	0	.08	
					50	432	-	-	-	
					62	480	325	8.6	5.8	
					65	492	-	-	-	
					68.5	508	311	24.3	5.6	Ignition
					70	710	266	73.0	1.7	
					71	650	298	40.3	2.7	
					75	528	-	-	-	

TABLE V. (CONTINUED)

Run No.	Atm Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temp. °C	Atmosphere Composition (mm Hg)			Remarks
	O_2	N_2	He				O_2	CO	CO_2	
315	20	-	80	569	30	305	-	-	-	
					40	362	114	0	0	
					58	440	-	-	-	
					68	480	96.2	4.4	5.6	
					75	505	-	-	-	Flash
					78.2	508	93.9	4.7	13.3	Flame
					78.8	528	73.0	2.6	23.9	
					81	600	75.2	3.5	25.9	
316	20	80	-	362	30	345	-	-	-	
					33	362	72.4	0	0	
					45	420	-	-	-	
					60	482	63.4	3.5	4.8	No Ignition
					70	520	46.7	2.6	11.5	
					73	528	44.5	3.7	11.5	
					80	508	60.3	7.7	3.9	
317	20	80	-	259	30	272	-	-	-	
					40	332	-	-	-	
					46	365	72.4	0	0	
					64	438	-	-	-	No Ignition
					75	482	49.2	3.1	5.2	
					85	530	40.7	1.1	18.2	
					90	520	44.2	4.3	10.8	

TABLE V. (Concluded)

Run No.	Atm Composition (%) O₂	N₂	He	Pressure (mm Hg)	Time (Min)	Sample Temp. °C	Atmosphere Composition (mm Hg) O₂	CO	CO₂	Remarks
318	100	-	-	760	30	318	-	-	-	
					38	365	760	-	-	
					50	422	-	-	-	
					60	452	-	-	-	
					67	480	751	9.9	18	
					68.7	485	689	8.2	22.4	Ignition
					70	890	592	3.1	79.3	
					71	730	608	5.3	64.7	
319	20	80	-	760	30	348	-	-	-	
					33	365	152	-	-	
					40	392	-	-	-	
					50	442	-	-	-	
					60	480	141	5.4	3.8	
					69.2	515	126	5.3	6.7	Ignition
					71	600	123	1.0	24.6	
					73	580	126	2.0	22.8	

TABLE VI.   SPONTANEOUS IGNITION TEMPERATURE OF MIL-H-8446B HYDRAULIC FLUID
SAMPLE VOLUME: 1/2 CC LIQUID

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (l/min)	S.I.T. °C	Remarks
	O₂	N₂	He				
1001	100	--	--	760	4	262	
1004	100	--	--	569	3.2	265	
1007	100	--	--	569	3.2	263	
1007A	100	--	--	569	3.2	267	
1010	100	--	--	362	1.9	270	Second ignition, after 4th injection at 278 °C
1013	100	--	--	259	1.3	309	Second ignition at 300 °C.
1002	60	40	--	760	4	271	
1005	60	40	--	569	3.2	280	
1005A	60	40	--	569	3.2	278	Second ignition at 278 °C.
1018	60	40	--	362	1.9	353	Second ignition at 340 °C, 3rd & 4th at 340 °C & 337 °C.
1014A	60	40	--	259	1.3	394	Second ignition at 400 °C, 3rd & 4th at 410 °C & 422 °C.
1014B	60	40	--	259	1.3	350	
1014C	60	40	--	259	1.3	361	Second ignition at 365 °C
1003	20	80	--	760	4	353	
1006	20	80	--	569	3.2	439	
1006A	20	80	--	569	3.2	410	Second ignition at 415 °C.
1012	20	80	--	362	1.9	492	
1012A	20	80	--	362	1.9	No Ignition	Tray temperature at 498 °C.
1015	20	80	--	259	1.3	No Ignition	
1008	60	--	40	569	3.2	272	
1009	20	--	80	569	3.2	399	
1009A	20	--	80	569	3.2	385	
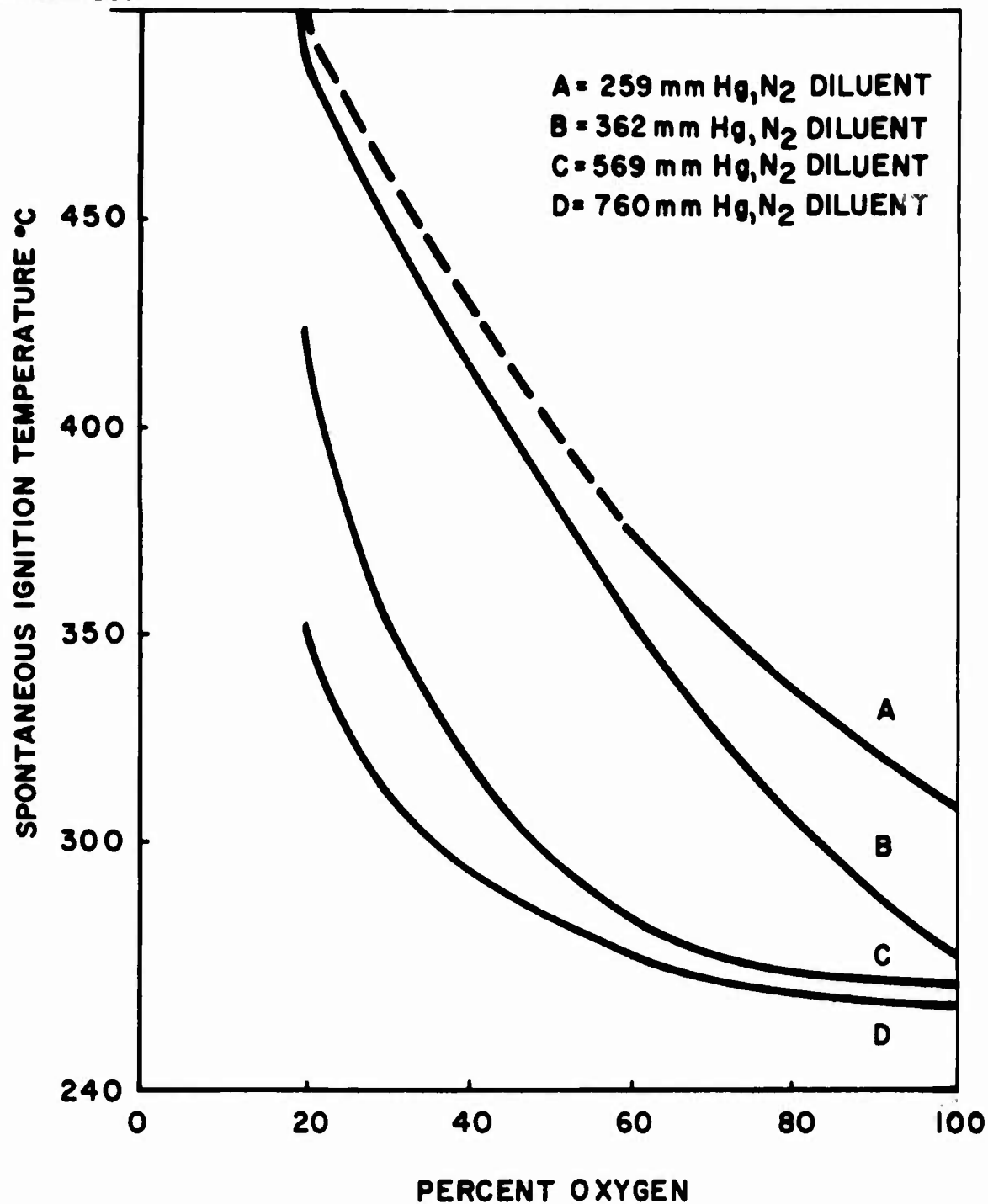
FIGURE 8. Spontaneous Ignition Temperature of MIL-H-8446B Hydraulic Fluid as a Function of Oxygen Concentration at Various Total Ambient Atmospheric Pressures(Sample: 1/2 cc Volume.)

The data clearly indicates that the observed S.I.T. is a direct function of the oxygen concentration and is virtually independent of the nature of the diluent in the ambient atmosphere. At low oxygen concentrations, substituting helium for nitrogen does lower the S.I.T. by approximately 8%.

(e) JP-6

Spontaneous Ignition Temperatures for JP-6 were obtained through the same techniques as employed for the hydraulic fluid tests. In this case, however, the volume of the test sample was increased to 1 cc. This increased volume permitted the utilization of the test specimen thermocouple unit to record the sample temperatures. The experimental S.I.T. values, given in Table VII, are the temperatures of the liquid surface at the point of ignition.

Evaluation of the data indicates that there is no clearly defined dependency of the S.I.T. values upon the oxygen concentration. Three different oxygen containing atmospheres were employed for this test series. Within each grouping there is a decided overlapping of the data, as is shown in Table VII. Quite possible, this "consistency" is due to the cooling effect of the vaporizing test fluid, as sensed by the sample test thermocouple. If so, the data does not reflect actual S.I.T. values. The only indication that the S.I.T. is oxygen concentration dependent is when comparing the results obtained between the 100% oxygen atmosphere data and the 20% oxygen atmosphere data.

Substitution of the nitrogen diluent by helium does not result in any significant change in the observed S.I.T. value.

(f) Viton A-Elastomer

The results of the experimental evaluation of the Spontaneous Ignition Temperature of MIL-R-25897C -- Class 1 Viton A-Elastomer are tabulated in Table VIII. The tests were performed using a "stack" of the material. Each "stack" consisted of two, one inch squares of the elastomer, each square being 1/16 inch thick. Previous comments made with reference to "stacked" test specimens are applicable here when reviewing the data.

The ignition behavior of the test samples is a function of the partial pressure of oxygen. At partial pressures of 450 mm Hg or greater, ignition was manifested by the appearance of a flame. At lower partial pressures of

TABLE VII. SPONTANEOUS IGNITION TEMPERATURE OF JP-6
SAMPLE: 1 CC VOLUME

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (1/min)	S.I.T. °C	Remarks
	O_2	N_2	He				
1101	100	--	--	760	4	272	
1101A	100	--	--	760	4	255	
1104	100	--	--	569	3.2	242	Value appears low
1104A	100	--	--	569	3.2	265	Second ignition at 260 °C
1107	100	--	--	569	3.2	255	
1110	100	--	--	362	1.9	256	
1110A	100	--	--	362	1.9	258	
1113	100	--	--	259	1.3	258	
1102	60	40	--	760	4	278	Second ignition at 280 °C
1102A	60	40	--	760	4	255	Second ignition at 258 °C
1105A	60	40	--	569	3.2	278	Second ignition at 278 °C
1108	60	40	--	569	3.2	260	
1111	60	40	--	362	1.9	262	Second ignition at 262 °C
1114	60	40	--	269	1.3	262	
1103	20	80	--	760	4	288	*
1103A	20	80	--	760	4	274	Second ignition at 278 °C
1106	20	80	--	569	3.2	278	Second ignition at 272 °C
1109	20	--	80	569	3.2	272	
1112A	20	80	--	362	1.9	--	No ignition
1112B	20	80	--	362	1.9	290	
1115	20	80	--	259	1.3	--	No ignition
1115A	20	80	--	259	1.3	--	No ignition

* Second ignition at 298 °C,
3rd ignition at 295 °C

TABLE VIII. SPONTANEOUS IGNITION TEMPERATURE OF VITON A--ELASTOMER
DIMENSIONS--2 PIECES OF 1 x 1 x 1/16 INCH MATERIAL

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (l/min)	Heating Rate °C/min	S.I.T. °C	Remarks
	O_2	N_2	He					
401	100	--	--	760	4	4.1	460	Sample crusty at end; No change in shap.
416	100	--	--	760	4	--	458	Sample "soaked" in 100% oxygen gas
421	100	--	--	760	4	--	455	for 30 days.
422	100	--	--	760	4	--	462	
404	100	--	--	569	3.2	4	463	
407	100	--	--	569	3.2	4	472	
410	100	--	--	362	1.9	4	480	Glow, no flame
413	100	--	--	259	1.3	4	540	
423	100	--	--	259	1.3	--	470	
402	60	40	--	760	4.0	4.1	462	
405	60	40	--	569	3.2	4	480	
418	60	40	--	569	3.2	4	470	
411	60	40	--	362	1.9	5	540	Glow, no flame
403	20	80	--	760	4	5	545	Glow, no flame
417	20	80	--	760	4	--	535	Glow, no flame
406	20	80	--	569	3.2	4	No ignition	
412	20	80	--	362	1.9	--	No ignition	Slight exothermic reaction
420	20	80	--	362	1.9	--	No ignition	
414	60	40	--	259	1.3	--	No ignition	
415	20	30	--	259	1.3	--	No ignition	
408	60	--	40	569	3.2	5	475	
419	60	--	40	569	3.2	--	485	
409	20	--	80	569	3.2	3.5	552	Glow, no flame

oxygen, ignition was manifested by the glowing of the sample surface, similar to that of burning charcoal.

The data clearly indicates the direct relationship between the observed S.I.T. and the oxygen concentration. This dependency is illustrated by Figure 9 . Substitution of nitrogen by helium had no significant effect upon the S.I.T. of Viton A. Exposure of the material to 100% oxygen atmospheres for thirty days prior to testing produced no observable change in the S.I.T. of Viton A.

Analyses of the ambient atmosphere within the reaction chamber were carried out for six of the experimental tests. Table IX presents this data. The analytical results show that:

1. The partial pressure of oxygen decreases markedly prior to ignition.
2. The carbon monoxide concentration is a maximum immediately prior to ignition.
3. At the onset of ignition, the carbon dioxide concentration increases rapidly, reaching a maximum shortly after the appearance of the flame.

It is noted that although the analyses did not include other compounds present in the ambient atmosphere, the presence of HF within the reaction chamber was demonstrated by the slightly etched appearance of the viewing port window at the conclusion of these runs.

(g) Nylon

Table X presents the data for the Spontaneous Ignition Temperature of MIL-C-7219, Type III Nylon Fabric. The individual test specimens consisted of fourteen layers of the nylon fabric, each layer being one inch square. As was already noted in the discussion of the polyvinychloride data, such test specimens lead to the inclusion of a nonreproducible variable. The apparent overlap and spread of the data, given in Table X, probably arises from this variable degree of compaction.

Visual observation of the individual tests indicate that the ignition and combustion of the material are a direct function of the partial pressure of oxygen. Above a partial pressure of oxygen of 350 mm Hg, ignition is
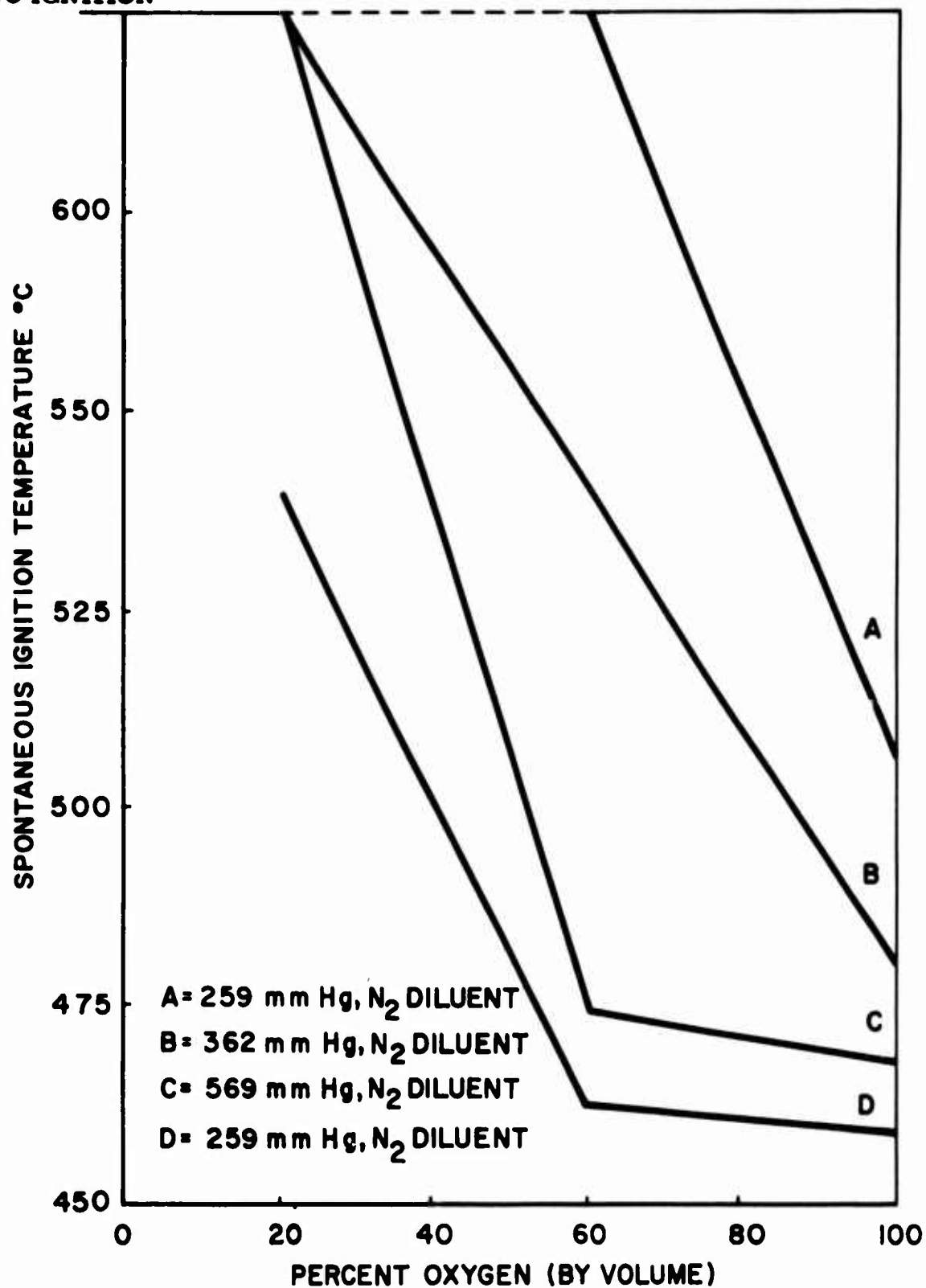
FIGURE 9. Spontaneous Ignition Temperature of Viton A--Elastomer as a Function of Oxygen Concentration at Various Ambient Atmospheric Pressures.

TABLE IX. TEMPERATURE AND GAS PHASE COMPOSITION AS A FUNCTION OF TEST TIME FOR VITON-A ELASTOMER

Run No.	Atm. Composition (%) O_2	N_2	He	Pressure (mm Hg)	Time (Min)	Sample Temperature (°C)	Atmosphere Composition (mm Hg) O_2	CO_2	CO
401	100	--	--	760	20	80	760	0	0
					45	230	760	0	0
					60	330	760	0.05	0.15
					75	422	755	3.5	2.5
					83.3	460	740	15.1	5.3
					85	770	--	--	--
					86	795	680	75.5	4.2
					88	848	--	--	--
					90.3	600	725	31.2	4.7
402	60	40	--	760	30	292	456	0	0
					40	352	456	0	0
					50	410	456	0.2	0.3
					60	452	450	3.9	2.2
					61.8	462	441	9.0	5.8
					65	688	414	34.2	6.9
					72	590	424	23.9	7.9
					75	508	--	--	--
403	20	80	--	760	40	328	151	0	0
					60	425	150	0.5	0.3
					70	455	145	4.1	3.0
					77	500	125	17.5	9.7
					81	540	136	6.6	7.6
					88	545	141	5.1	4.9
					92	545	--	--	--
					95	560	--	--	--
					100	568	--	--	--
					105	560	--	--	--
					110	552	--	--	--

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TABLE IX. (CONTINUED)

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temperature (°C)	Atmosphere Composition (mm Hg)		
	O_2	N_2	He				O_2	CO_2	CO
405	60	40		569	45	358	342	0	0
					70	458	337	2.7	2.2
					76	515	315	17.3	9.6
					80	560	305	24.6	3.9
					83	660	309	26.0	6.2
					85	670	--	--	--
					88	665	--	--	--
					92	615	--	--	--
					94.8	560	--	--	--
408	60	40		569	35	375	342	0	0
					51	452	331	5.2	5.8
					51.6	475	288	43.4	9.5
					58	630	268	66.9	7.4
					64	660	300	34.8	7.2
					66.5	620	--	--	--
					68	585	--	--	--
409	20	--	80	569	25	350	113	0	0
					45	460	107	2.9	2.6
					51	505	79	23.7	10.7
					60	600	79	29.0	4.9
					68	640	80	28.3	5.2
					75	590	--	--	--

TABLE X. SPONTANEOUS IGNITION TEMPERATURE OF MIL-C-7219 TYPE III NYLON FABRIC
DIMENSIONS: 14 PIECES OF 1" SQUARES

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (1/min)	Heating Rate	S.I.T. °C	Remarks
	O_2	N_2	He					
501	100	--	--	760	4	7.5	392	Aged 30 days in 100% O_2
519	100	--	--	760	4	7.0	414	Aged 30 days in 100% O_2
520	100	--	--	760	4	7.5	420	
504	100	--	--	569	3.2	5.0		Second ignition at 430 °C
507	100	--	--	569	3.2	10.0	402	
510	100	--	--	362	1.9	--	No ignition	
502	60	40	--	760	4	8	412	Had second flame at 448 °C
505	60	40	--	569	3.2	5	502	Had double glow, second at 500 °C
517	60	40	--	569	3.2	4	508	
511	60	40	--	362	1.9	3.5	502	Had no flame, only "glow"
510A	100	--	--	362	1.9	11	430	
515	100	--	--	259	1.3	--	No ignition	
514	60	40	--	259	1.3	--	No ignition	
503	20	80	--	760	4	--	No ignition	Sample reduced to carbon
516	20	80	--	760	4	--	No ignition	
518	20	80	--	569	3.2	--	No ignition	Black film on tray
506	20	80	--	569	3.2	--	No ignition	All samples consumed, carbon trace
512	20	80	--	362	1.9	--	No ignition	Black residue in system
508	60	--	40	569	3.2	5	495	Glow, no flame
509	20	--	80	569	3.2	--	No ignition	Sample consumed, carbon trace remains

followed by an intense, brilliant flame. Below that oxygen concentration ignition is evidenced by a weak "glowing" of the sample surface. Pre-conditioning the fabric, in 100% oxygen atmospheres for thirty days prior to testing, has no observable effect upon the S.I.T. of the nylon.

Figure 10 illustrates the dependency of the S.I.T. of nylon upon the oxygen concentration within an ambient atmosphere. These curves were obtained by averaging the individual S.I.T. values obtained at specific oxygen concentrations and total pressures.

Table XI presents the composition of the ambient atmospheres within the reaction chamber, for various experimental runs, during the test period. The analytical results are similar to those previously reported. At ignition, the oxygen concentration decreases sharply, the carbon monoxide concentration maximizes, while the CO_2 concentration sharply increases, continuing to do so during the subsequent combustion period.

(h) Dacron

Spontaneous Ignition Temperatures for 7400 Dacron are reported in Table XII. As with the previous fabrics tested, the dacron test samples consisted of stacked samples, and are subject to the same experimental difficulties as noted above for other such samples. The tabulated data does show that the observed S.I.T. values are a function of the oxygen concentration, increasing in value as the oxygen concentration decreases. This is graphically illustrated by Figure 11. In Figure 11, curve B is based upon (1) the observed 100% oxygen data point, and (2) the fact that for 20% oxygen at 569 mm Hg, there was no ignition. It is logical, then, that for 20% oxygen at 362 mm Hg total ambient pressure, there would be no ignition. Curve B is probably low at the 60% oxygen level.

The substitution of nitrogen by helium has a marked effect on the S.I.T. of Dacron, raising the ignition energy requirements of the material. In the presence of helium as a diluent, the sample pyrolyzes, but does not ignite. Preconditioning the sample in 100% oxygen atmospheres for 30 days prior to test lowers the S.I.T. of the material.
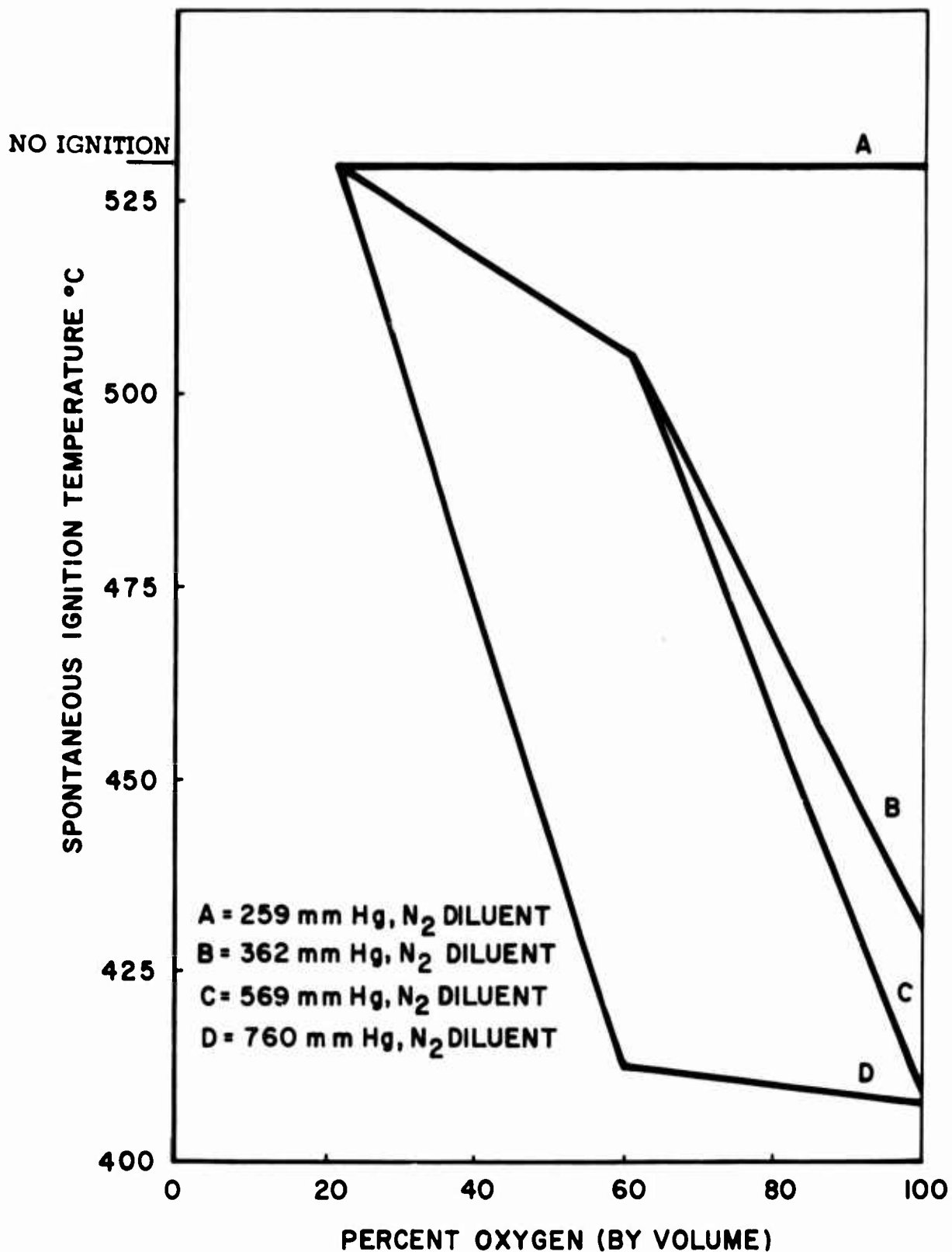
FIGURE 10. Spontaneous Ignition Temperature of Type III Nylon Fabric as a Function of Oxygen Concentration at Various Total Ambient Atmospheric Pressures.

TABLE XI. TEMPERATURE & ATMOSPHERE COMPOSITION OF MIL-C-7219
TYPE III NYLON FABRIC IGNITION TESTS AS A FUNCTION OF TIME

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temperature °C	Atm. Composition (mm Hg)			Remarks
	O₂	N₂	He				O₂	CO	CO₂	
520	100	--	--	760	30	335	760			Puffed & boiling.
					36	385	709.4	0.399	0.093	Gas sample cloudy.
					40	410	620.7	3.536	3.492	Very slow boiling.
					41:40	420	707.5	6.452	21.21	*
					42:30	520	--	--	--	
					44	445	685.4	2.154	24.69	Gas sample clear.
515	100	--	--	760	30	278	760	--	--	Completely melted & starting to boil.
					38	358	705.2	0.792	1.402	Boiling harder.
					45	400	567.6	9.414	3.408	Slower boil.
					50:40	430				
					51:20	540				Ignition bright flame.
					53	445	584.7	2.037	14.405	Out
510A	100	--	--	362	25	390	362	3.968	7.566	
					29:10	430	364.6	--	--	**
					29:50	605	--			Out
					30:40	490	307.7	2.312	60.05	Glow, short duration.
					33	475	400.1	1.751	48.44	Heaters off.

* Ignition, bright flame, fast dying out.
** Sudden ignition, large bright flame.

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TABLE XII. SPONTANEOUS IGNITION TEMPERATURE OF 7400 DACRON FABRIC
DIMENSIONS: 19 PIECES, EACH 1" x 1" SQUARES

| Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (l/min)	Heating Rate °C/min	S.I.T. °C	Remarks
	O_2	N_2	He					
601	100	--	--	760	4	8	448	
604	100	--	--	569	3.2	5.5	488	Second ignition at 492°C
604A	100	--	--	569	3.2	7.3	468	
607	100	--	--	569	3.2	5	500	
610	100	--	--	362	1.9	6	610	
613	100	--	--	259	1.3	--	No ignition	
617	100	--	--	760	4	--	432	O_2 soaked 30 days
616	100	--	--	760	4	--	438	O_2 soaked 30 days
602	60	40	--	760	4	6.5	468	Also 512 and 515. This is due to "stacking" of sample
605	60	40	--	569	3.2	6.5	508	
603	20	80	--	760	4	--	No ignition	
606	20	80	--	569	3.2	--	No ignition	
608	60	--	40	569	3.2	--	No ignition	

40
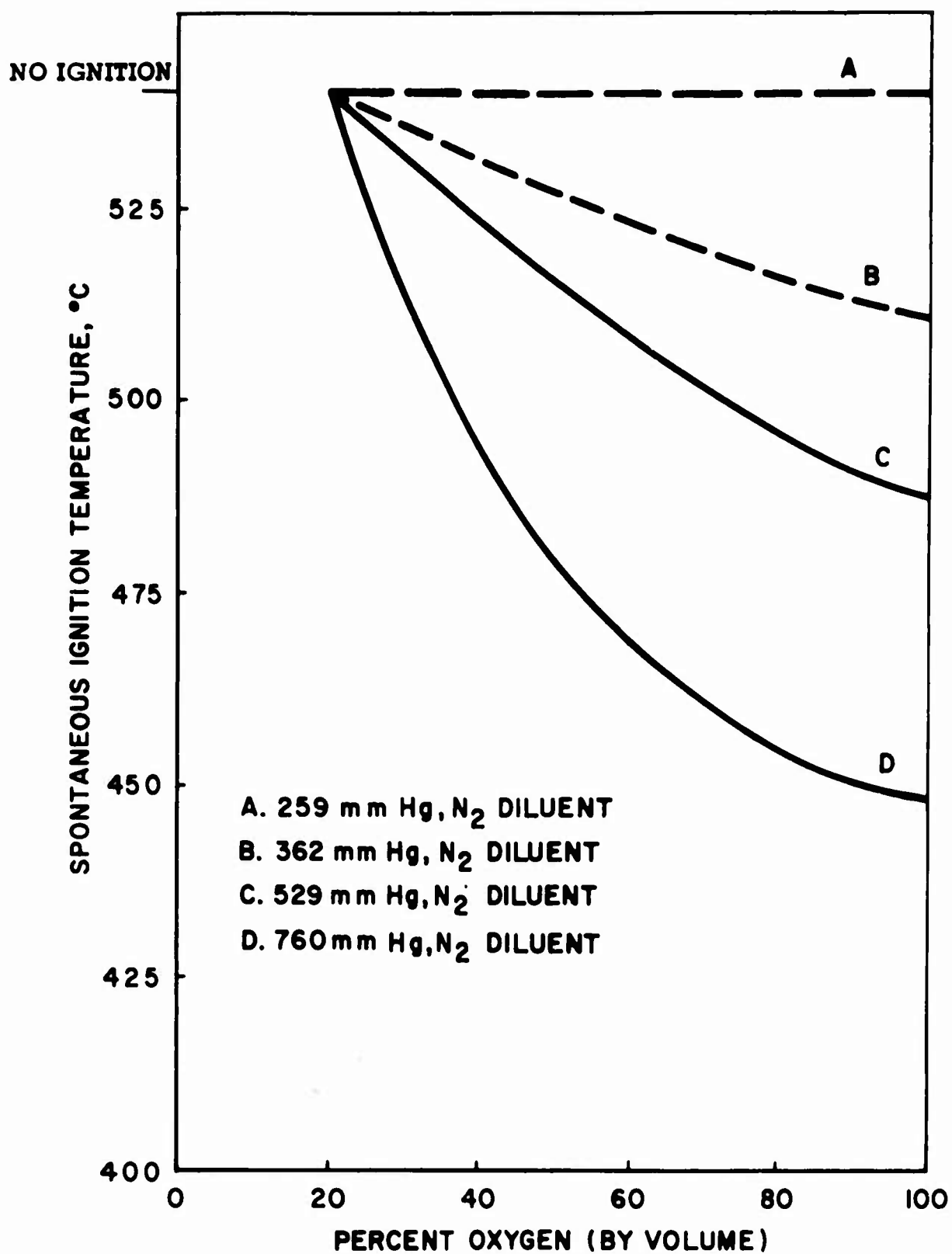
FIGURE 11. Spontaneous Ignition Temperature of 7400 Dacron Fabric as a Function of Oxygen Concentration at Various Total Ambient Atmospheric Pressures.

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Analyses of the reaction chamber atmosphere for several of the test runs are given by Table XIII. It is noted that appreciable carbon monoxide and carbon dioxide is present prior to ignition in virtually every test cited, with the CO_2 concentration increasing and the CO concentration decreasing at the onset of combustion.

(i) White Orlon Fabric

The Spontaneous Ignition Temperature determinations made with woven Orlon fabric were carried out using stacks of nine one inch squares of the fabric as the test samples. As is evident from the data given in Table XIV, there is a large degree of overlapping of the S.I.T. values for a given oxygen concentration as well as between the different oxygen concentrations employed for this test series. This is due to the variable degree of compaction exhibited by the "stacked" test samples.

Nevertheless, the data shows that the observed S.I.T. is a function of the prevailing oxygen concentration, increasing as the partial pressure of oxygen in the ambient atmosphere decreases. Figure 12 illustrates this quite clearly.

Substitution of nitrogen by helium, as the atmospheric diluent, produces no significant change in the observed S.I.T. values. Presoaking the test specimen in 100% oxygen atmospheres for 30 days prior to test, also produces no significant change in the observed S.I.T. values.

Results of the analysis of the ambient test atmospheres for several tests, as a function of time, are given by Table XV. The behavior of the $O_2:CO:CO_2$ ratio during each run is similar to that exhibited by test atmospheres analyzed for previously reported test specimens.

(j) Molded Teflon

Three Spontaneous Ignition Temperature determinations were carried out using molded teflon. No ignition was observed with teflon in atmospheres of 100% oxygen at pressures ranging from 259 to 760 mm Hg. The relationship between temperature and atmospheric composition is shown in Table XVI. The gas chromatographic analysis of the atmosphere did not indicate the presence

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TABLE XIII. TEMPERATURE & ATMOSPHERE COMPOSITION OF NO.
7400 DACRON IGNITION TESTS AS A FUNCTION OF TIME

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temperature °C	Atm. Composition (mm Hg)			Remarks
	O_2	N_2	He				O_2	CO	CO_2	
601	100	--	--	760	20	242	760	--	--	
					31	352	760	--	--	
					42	445	733	10.47	15.87	
					42.10	448	744	9.76	6.10	Ignition
					43.40	465	680	9.15	69.92	Flame out
602	60	40	--	760	36	368	456	--	--	
					41	408	453	1.11	1.88	
					47	448	439	6.04	10.55	
					50.30	468	411	7.76	37.06	Ignition
					48	520	441	3.05	11.33	
604	100	--	--	569	45	410	566	0.99	1.72	
					50	448	558	3.91	6.39	
					55	478	555	4.90	9.77	
					56.30	488	525	3.67	39.69	Ignition
					59	501	550	3.23	15.43	
604A	100	--	--	569	45	432	558	4.31	5.95	
					50.10	468	537	5.91	25.82	Ignition
					51	475	528	6.10	34.21	Flame out
					54.10	492	544	5.42	19.31	
605	60	40	--	569	30	408	338	1.11	1.91	
					36	452	325	5.94	12.49	
					43.05	508	318	10.50	11.55	Ignition flash
					44	512	313	5.67	21.50	

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TABLE XII. (CONTINUED)

Run No.	Atm. Composition (%) O₂	N₂	He	Pressure (mm Hg)	Time (Min)	Sample Temperature °C	Atm. Composition (mm Hg) O₂	CO	CO₂	Remarks
610	100	--	--	362	35	444	344	8.01	9.30	
					40	482	338	8.90	14.21	
					44	510	325	10.10	26.73	Ignition
					45	515	322	11.98	28.04	
616	100	--	--	760	40	378	758	0.43	0.78	
					47.45	438	714	5.64	39.75	Ignition
					49	448	720	5.64	33.96	
					53	468	737	2.83	19.50	
617	100	--	--	760	35	385	759	0.65	0.63	
					38	415	755	1.82	2.69	Ignition
					40.05	432	714	4.93	40.97	Out
					41	445	701	5.63	52.77	
					45	472	742	3.97	13.21	

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TABLE XIV. SPONTANEOUS IGNITION TEMPERATURE OF ORLON FABRIC
DIMENSIONS: 9 PIECES OF 1" SQUARES

| Run No.	Atm. Composition (%)			Pressure (mm Hg)	Flow Rate (1/min)	Heating Rate °C/min	S.I.T. °C	Remarks
	O$_2$	N$_2$	He					
701	100	--	--	760	4	5	518	Quite a spread in values. Most likely due to degree of compaction.
701A	100	--	--	760	4	6.5	560	
704	100	--	--	569	3.2	5	590	
710	100	--	--	362	1.9	3	660	Glow only, no flame
713	100	--	--	259	1.33	--	No Ignition	
716	100	--	--	760	4	3.5	515	Soaked in O$_2$ – 30 days, No apparent effect on S.I.T.
717	100	--	--	760	4	5	500	
702	60	40	--	760	4	5	600	
705	60	40	--	569	3.2	5	568	Glow
703	20	80	--	760	4	--	No Ignition	
715	20	80	--	259	1.4	--	No Ignition	
708	60	--	40	569	3.2	2	580	Red glow only

45
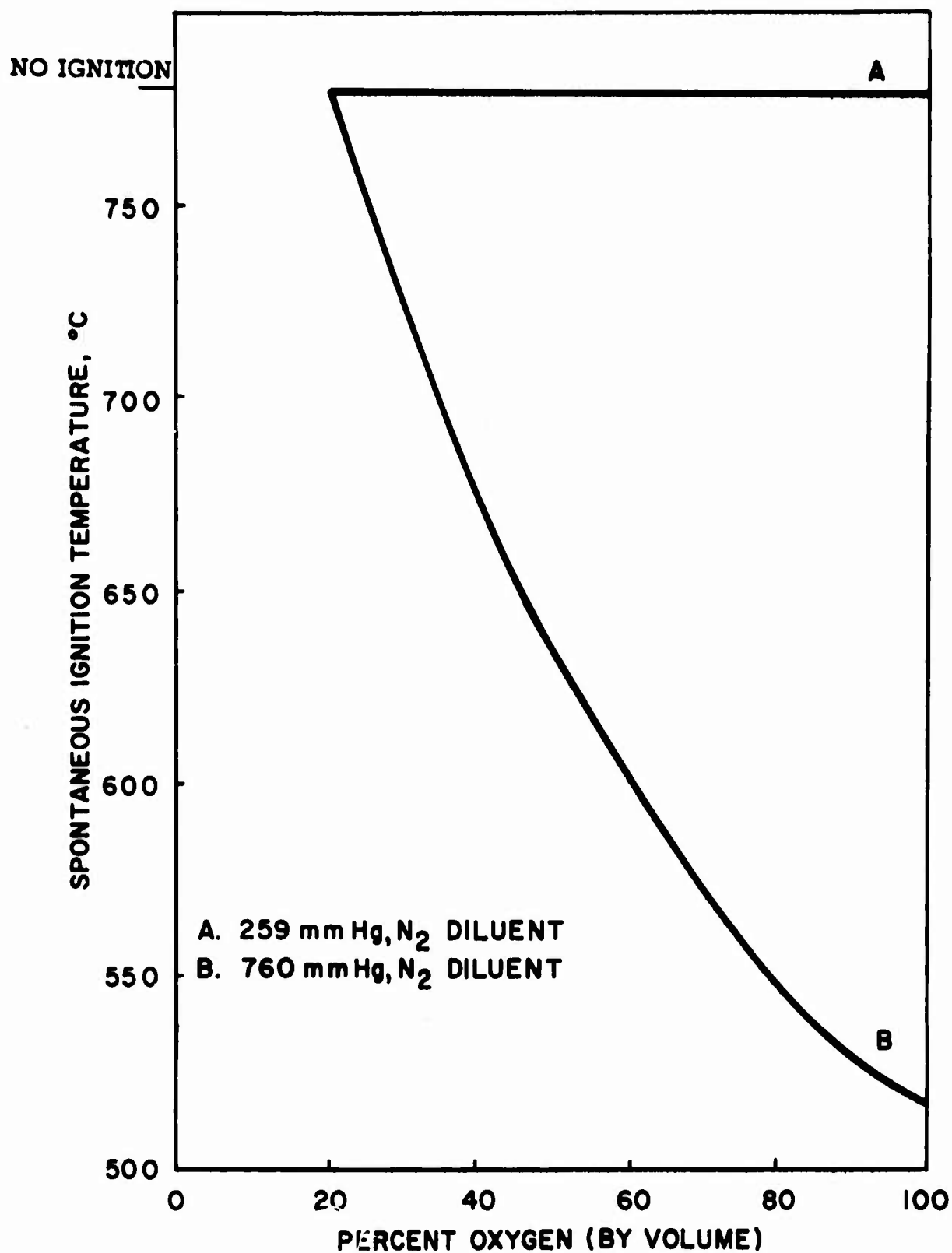
FIGURE 12. Spontaneous Ignition Temperature of Orlon Fabric as a Function of Oxygen Concentration at Various Total Ambient Atmospheres.

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TABLE XV. TEMPERATURE & ATMOSPHERE COMPOSITION OF WHITE
ORLON IGNITION TESTS AS A FUNCTION OF TIME

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temperature °C	Atm. Composition (mm Hg)			Remarks
	O_2	N_2	He				O_2	CO	CO_2	
704	100	--	--	569	24	320	569	--	--	
					25.30	350	569	--	--	
					45	450	567	0.40	1.44	
					52	515	563	0.68	5.41	
					54	590	546	1.57	21.28	
					58	850	565	3.57	--	Ignition
716	100	--	--	760	27:20	280	760	--	--	
					50	448	742	3.23	4.41	
					55	500	747	4.65	7.83	
					55:40	515	735	5.08	19.03	
					57	912	713	4.62	42.38	
					60:20	490	723	5.76	30.67	Ignition
717	100	--	--	760	24	372	759	0.15	0.53	
					40	425	757	0.74	1.47	
					49:55	520	742	1.66	15.43	
					51	925	729	1.54	29.17	
					56	495	723	1.23	34.87	Ignition
708	60	--	40	563	30	290	341	--	--	
					32	335	341	--	--	
					55	432	336	2.46	2.32	
					64	475	333	3.73	4.32	
					68	488	331	4.10	5.92	
					79	500	330	4.00	6.98	
					85	640	326	5.05	9.55	
					87:30	480	326	4.93	9.30	Visible glow

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TABLE XV. (CONTINUED)

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temperature °C	Atm. Composition (mm Hg)			Remarks
	O_2	N_2	He				O_2	CO	CO_2	
710	100	--	--	362	20	288	362	--	--	
					22	360	361	--	0.59	
					35	428	360	0.65	0.72	
					40	455	360	0.65	1.41	
					45	492	357	1.29	3.10	
					52	540	351	3.11	7.76	Visible glow
					55:30	760	324	4.19	33.21	

TABLE XVI. TEMPERATURE & ATMOSPHERE COMPOSITION OF
TEFLON IGNITION TESTS AS A FUNCTION OF TIME

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time (Min)	Sample Temperature °C	Atmosphere Composition (mm Hg)		
	O_2	N_2	He				O_2	CO	CO_2
801	100	--	--	760	25	288	760	--	--
					32	330	760	--	--
					40	380	759	0.28	--
					45	408	759	0.31	0.25
					50	428	759	0.31	0.50
					55	452	758	0.62	0.94
					60	457	758	0.62	0.94
802	20	80	--	760	40	355	152	--	--
					60	448	152	--	--
					65	460	142	2.65	7.04
803	20	80	--	259	30	348	52	--	--
					45	432	51	0.06	0.44
					52	462	51	0.15	0.88

of any degradation products. It is well known that the pyrolysis of teflon produces tetrafluoroethylene, small quantities of tetrafluoromethane and traces of higher fluorinated hydrocarbons. The lack of detection resulted from the use of column packing material in the chromatograph selected to measure specifically normal combustion atmosphere constituents, not fluorinated hydrocarbons.

(k) Acrylic Fabric

Two ignition tests were carried out on No. 1104 sunbrella acrylic fabric. The acrylic fabric ignited at a sample temperature of $410^{\circ}C$ at oxygen pressures of 760 mm (100% O_2 atmosphere) and 461 mm (60% oxygen atmosphere). The temperature of the tray which was in contact with the sample, however, was only $285^{\circ}C$ for the 760 mm oxygen pressure test and $325^{\circ}C$ for the 461 mm oxygen pressure test. The sample temperature lagged behind the tray temperature until it reached $245^{\circ}C$ at which time a highly exothermic reaction was observed. This reaction resulted in a rapid increase in the sample temperature culminating in visible ignition at $410^{\circ}C$. The results of these two tests are insufficient to characterize the S.I.T. of the acrylic fabric.

5. Summary of Results

Spontaneous Ignition Temperatures have been evaluated for eleven materials utilizing the Dynamic Science Combustion Monitor, Model 164. The test results show that the S.I.T. is an inverse function of the oxygen concentration, except for JP-6, Teflon, and Acrylic Fabric. Teflon did not ignite under the test conditions, including 100% oxygen atmospheres. Acrylic Fabric was spot checked only. Data for JP-6 was subject to an experimental difficulty which rendered the results somewhat ambiguous.

B. PHASE II. IGNITION AND COMBUSTION BEHAVIOR OF MATERIALS AS A FUNCTION OF GRAVITY INCLUDING THE EFFECTS OF VARIOUS EXTINGUISHANTS

1. Introduction

All of the flammable characteristics which materials exhibit under experimental testing at terrestrial gravity are a consequence of (1) the initial thermal

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response of the material and (2) the subsequent chemical reactions with the available oxidant. For solids, the sequence of events leading to ignition and steady-state combustion may be represented as follows.

Under initial thermal stress, the solid undergoes pyrolysis, liberating reactive pyrolytic vapors. These vapors physically mix with the surrounding atmosphere and enter a chemical reaction with the oxidant, at a rate proportional to the concentrations of both the vapor and oxidant. This chemical activity liberates additional heat which, when sufficient, ignites the vapors in the vicinity of the solid surface. A portion of the heat of combustion is fed back to the solid, thereby maintaining or enhancing the pyrolytic process. The remainder of the heat is taken up by the product gases, radiated, or both. The hot gases being of lower density rise and leave the flame zone, at the same time cooler atmospheric gases enter it, thus maintaining the supply of oxidant at the flame zone. This picturization shows that the combustion process is directly related to oxidant concentration as being supplied by convective forces.

At zero gravity the above process is, most likely, severely altered because of the absence of convective forces. The experimental tests carried out in this phase of the work were designed to define this variable by comparing the burning characteristics of materials under one gravity and zero gravity conditions. The zero gravity tests are aimed to simulate conditions similar to those anticipated for the Manned Orbiting Laboratory. These tests were also designed to determine the effectiveness of several fire extinguishing agents under the test environmental conditions.

2. Apparatus

The experimental apparatus, employed for both the one gravity and zero gravity programs, was the NASA zero gravity test chamber. This chamber has a volume of 0.75 cubic feet which provides a region of 10 inches in diameter for the flame. One end of the chamber is fitted with a pyrex window, one inch thick, so as to permit photographing of the reaction occurring within the chamber. Samples were positioned, by means of a holding device, 6.5 inches from the rear end of the chamber which consisted of a grid background. An

eight inch Nichrome No. 26 wire was looped about one portion of the sample and attached to the electrical leads which extended through the grid background. This igniting wire was energized by a 28 volt source. Its resistance was 1.78 ohms.

For tests involving the application of extinguishing agents, a nozzle arrangement was placed within the chamber such that its discharge was directed at the burning sample material. The rate of discharge of the extinguishants was controlled by the degree of pressurization of the extinguishant container volume.

Figure 13 illustrates the experimental apparatus.

3. Procedure

The sample material is first secured to the sample holder which is a component part of the removable rear grid end of the chamber. This is followed by looping the igniting nichrome wire about one portion of the sample. The entire assembly is placed within the reaction chamber which is then sealed and leak checked. At this point the chamber is pressurized with the desired ambient atmosphere, evacuated, and then refilled with this atmosphere up to the required operating pressure for a particular run. Three operating pressures are utilized for this test series, namely, 256, 386, and 569 mm Hg. Initial ambient atmospheres range from 100% oxygen to 50-50 mixtures of oxygen-nitrogen and oxygen-helium.

For tests involving the application of extinguishing agents, three different classes of extinguishants were tested. The amounts and rate of application of each is given below:

Agent	Amount	Rate of Application
CF_3Br (Halon 1301)	3 grams	2 grams/second
H_2O	30 grams	20 grams/second
Protein Foam	30 grams	15 grams/second

GRID BACKGROUND

NICHROME WIRE
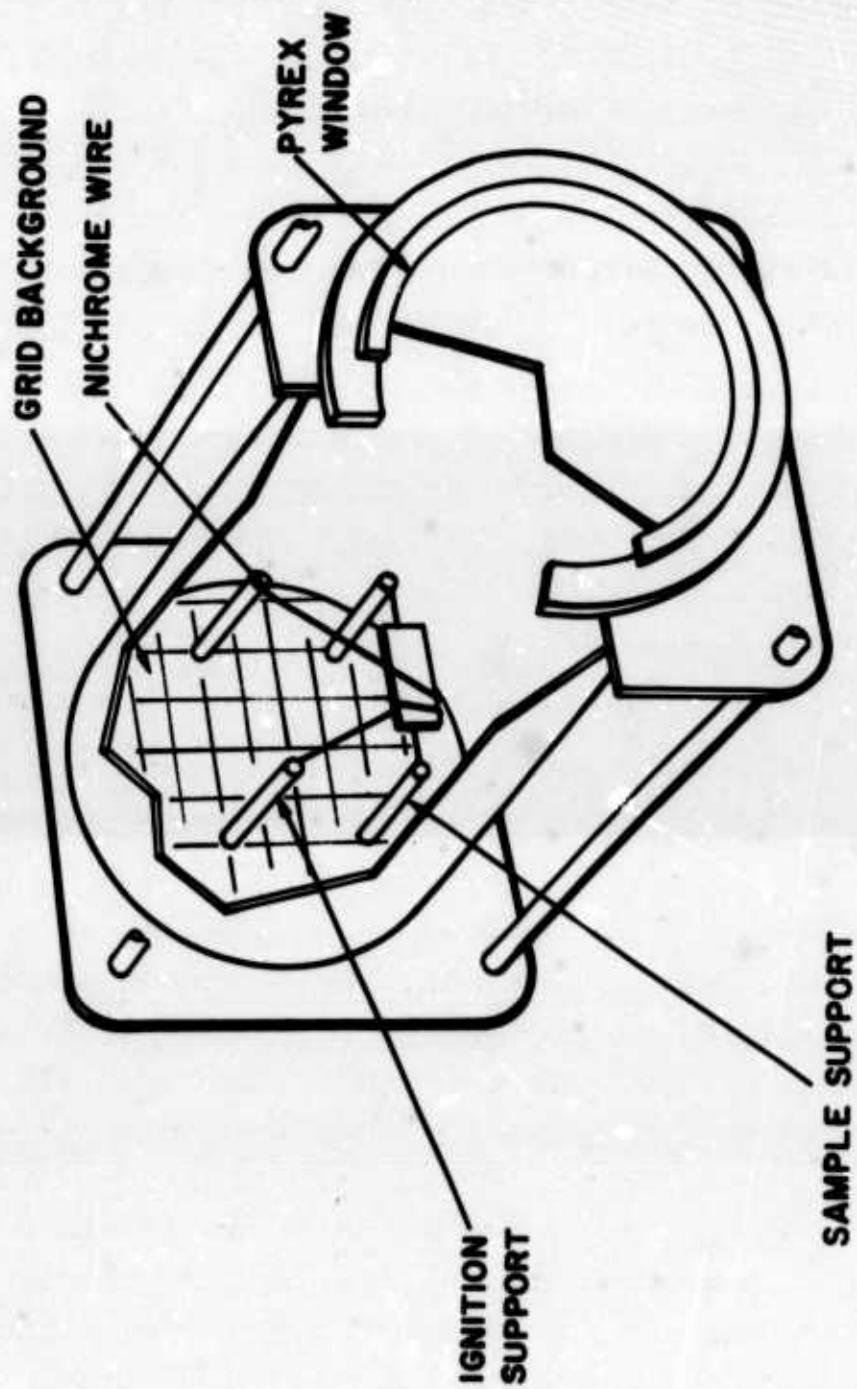
PYREX
WINDOW

IGNITION
SUPPORT

SAMPLE SUPPORT

FIGURE 13. NASA Zero Gravity Test Chamber.

As is evident, Protein Foam application is the longest (2 seconds). All extinguishants were admitted to the system approximately 3 seconds after actuation of the ignition circuit.

All test runs were recorded photographically.

4. Experimental Results

(a) Burning Times at One Gravity in the Presence and Absence of Extinguishing Agents.

Three materials were selected for this test series. They were polyethylene, Dacron fabric, and mineral oil. The solid samples are representative of those materials which must undergo pyrolytic degradation prior to their ignition and subsequent combustion. The liquid sample is a hydrocarbon of low volatility and is representative of materials which must only be vaporized prior to their ignition.

The specific test specimens employed were of the following dimensions:

polyethylene	1-1/4 x 1/4 x 1/8 inches
dacron fabric	1-1/4 x 1/4 inches
mineral oil	0.1 cc on asbestos string

Table XVII summarizes the data obtained for the experimental tests conducted in the absence of extinguishants. The behavior of the solid test samples is as anticipated, with the burning time decreasing as the oxygen concentration increases, in 100% oxygen atmospheres. The utilization of ambient atmospheres containing diluents increases the burning time relative to that observed for the 100% oxygen atmospheres. In the case of polyethylene, helium as a diluent exerts a greater retarding affect upon the combustion process than does nitrogen. This is evident by the larger increase in burning time in helium containing atmospheres than that noted for nitrogen containing atmospheres. An increase in the burning time indicates a corresponding decrease in the burning rate, hence helium containing atmospheres decreases the burning rate of polyethylene to a greater extent. The opposite effect is noted with regard to Dacron fabric test samples.

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TABLE XVII. COMBUSTION BEHAVIOR OF SELECTED MATERIALS AT ONE GRAVITY AS TESTED IN THE NASA ZERO GRAVITY TEST CHAMBER

Run No.	Material	Atm. Composition (%) O_2	N_2	He	Pressure (mm Hg)	Burning Time (Sec)	Remarks
1	Polyethylene	100	–	–	256	8.53	Burning time decreases as oxygen concentration increases.
2		100	–	–	386	8.4	
3		100	–	–	569	7.7	
4		50	–	50	256	10.4	Use of Helium as diluent increases burning time relative to that observed using nitrogen as diluent.
5		50	–	50	286	11.4	
6		50	–	50	569	10.0	
7		50	50	–	256	9.3	
8		50	50	–	386	9.3	
9		50	50	–	569	8.5	
10	Dacron	100	–	–	256	3.5	
11		100	–	–	386	3.5	
12		100	–	–	569	3.2	
13		50	–	50	256	5.3	
14		50	–	50	386	5.4	
15		50	–	50	569	6.21	
16		50	50	–	256	7.4	Burning time directly proportioned to oxygen concentration.
17		50	50	–	386	6.8	Use of nitrogen as diluent increases burning time relative to that observed using helium as diluent.
18		50	50	–	569	8.8	
19	Mineral Oil	100	–	–	256	8.7	
20		100	–	–	386	7.3	
21		100	–	–	569	7.9	
22		50	–	50	256	7.9	
23		50	–	50	386	5.8	
24		50	–	50	569	7.1	
25		50	50	–	256	9.7	Burning time longer in presence of nitrogen as diluent relative to use of helium as diluent
26		50	50	–	386	7.2	
27		50	50	–	569	9.4	

The observed results of the mineral oil test series are ambiguous. A dependency of the burning rate upon oxygen concentration is evident if one regards the extremes of the pressure ranges only. The presence of nitrogen as the atmospheric diluent has an apparent greater retarding effect upon the burning rate than does the helium containing atmospheres. It appears that the experimental difficulties experienced in preparation of the liquid sample, in terms of uniformity and reproducibility of application, make these results very qualitative at best.

Table XVIII represents the experimental data obtained for the same three test materials under similar initial ambient atmospheres and pressures but now subjected to the presence of the various extinguishants previously noted. The basic requirements of an extinguishing agent to be utilized within a manned flight vehicle cabin are:

1. The extinguishant must be capable of application under zero gravity conditions.

2. The extinguishant and its degration products must not be toxic or exhibit anesthetic effects.

3. The extinguishant and its degradation products must be noncorrosive, nor must it leave residues which would adversely affect cabin equipment.

Prior to the selection and testing of the three extinguishants noted in Table XVIII, an extensive literature survey was conducted in an effort to identify suitable candidate material. The above cited extinguishants were deemed the best in that they were thought to exhibit the necessary basic requirements listed above. For a complete discussion of this point see Reference 2.

Returning to Table XVIII, it is noted that the polyethylene burning time in 100% oxygen atmospheres exhibits the same dependency upon the oxygen concentration noted in Table XVII, even in the presence of the Halon 1301. However, the burning time is increased by approximately 50% for the low oxygen level tests. At 569 mm Hg oxygen pressure, the CF_3Br had no apparent effect upon the burning time. Use of the extinguishant in atmospheres

TABLE XVIII. BURNING CHARACTERISTICS OF SELECTED MATERIALS AT ONE GRAVITY AS TESTED IN THE NASA ZERO GRAVITY TEST CHAMBER IN THE PRESENCE OF VARIOUS EXTINGUISHING AGENTS

Run No.	Material	Extinguisher	Atm. Composition (%)			Pressure (mm Hg)	Burning Time (Sec)	Remarks
			O_2	N_2	He			
1	Polyethylene	CF_3Br	100	--	--	256	11.7	Negative. Sample consumed.
2			100	--	--	386	9.03	Negative. Sample consumed.
3			100	--	--	569	7.84	Negative. Sample consumed. Possible Br2 present.
4		H_2O	50	50	--	569	10.9	Negative. Sample consumed.
5			50	--	50	256	10.4	Negative. Sample consumed. Possible Br2 present
6			100	--	--	256	11.5	Negative. Sample consumed.
7			100	--	--	386	8.9	Negative. Sample consumed.
8			100	--	--	569	9.67	Negative. Sample consumed.
9			50	50	--	569	11.58	Negative. Sample consumed.
10			50	--	50	256	8.0	Negative. Sample consumed.
11		Foam	100	--	--	256	11.2	Negative. Sample consumed.
12			100	--	--	386	(4.3)	Run in apparent error.
13			100	--	--	569	11.2	Negative. Sample consumed.
14			50	--	50	256	0.54	Negative. Sample not entirely consumed. Consider positive.
15	Dacron	CF_3Br	100	--	--	256	6.1	Negative. Sample consumed.
16			100	--	--	386	6.3	Negative. Sample consumed.
17			100	--	--	569	4.28	Negative. Sample consumed.
18		H_2O	50	50	--	569	9.75	Positive. Some sample left.
19			50	--	50	256	3.5	Positive. Some sample left.
20			100	--	--	256	3.83	Negative. Sample consumed.
21			100	--	--	386	5.56	Negative. Sample consumed.
22			100	--	--	569	3.14	Negative. Sample consumed.
23			50	--	50	256	4.87	Negative. Sample consumed.
24			50	50	--	569	--	Negative. Sample consumed.

FIGURE XVIII. (CONTINUED)

Run No.	Material	Extinguisher	Atm. Composition (%)			Pressure (mm Hg)	Burning Time (Sec)	Remarks
			O_2	N_2	He			
25	Dacron	Foam	100	–	–	256	3.4	Positive. Sample not all consumed.
26			100	–	–	386	11.5	Negative. Sample consumed.
27			100	–	–	569	5.3	Negative. Sample not consumed.
28			50	50	–	569	––	Positive. Sample not consumed. No flame.
29			50	–	50	256	0.92	Positive. Sample not all consumed. Flameout < 1 sec.
30	Mineral Oil	CF_3Br	100	–	–	256	7.3	Negative. Sample consumed. Possible Br_2 present.
31			100	–	–	386	5.8	"
33			100	–	–	256	6.5	"
34		H_2O	50	50	–	569	7.3	Negative. Sample consumed.
35			50	–	50	256	1.14	Positive. Sample not all consumed. Flameout < 2 sec.
36			100	–	–	256	11.1	Negative. Sample all consumed.
37			100	–	–	386	11.9	"
38			100	–	–	569	3.8	"
39			50	50	–	569	9.86	Negative. Sample all consumed.
40			50	–	50	250	2.3	"
41		Foam	100	–	–	256	1.3	Run stopped. Negative. Sample consumed.
42			100	–	–	386	6.8	Negative. Sample consumed.
43			100	–	–	469	11.3	Positive. Sample not all consumed.
44			50	50	–	569	10.7	Negative. Sample consumed.
45			50	–	50	256	11.0	Positive. Sample not all consumed.

containing nitrogen as the diluent appears to increase the burning time by 37%. In helium containing atmospheres no appreciable change in burning time was observed. It is also noted that all the test materials were consumed in each of these tests. Therefore, the results are considered negative with respect to fire extinguishment. In addition, Br_2 was observed to be present in several of the runs, and at completion of this test series, it was observed that the test chamber was badly corroded.

The remaining experimental tests utilizing polyethylene were conducted employing foam and water as extinguishants. The protein foam agent provided a positive result when the test was conducted in 50-50 oxygen-helium atmospheres at low (256 mm Hg) pressure. This is a decided contrast to the analogous run reported in Table XVII. It also caused the burning time to increase by over 50% for the 100% O_2 test at 569 mm Hg pressure. The difficulty with this extinguishant is that it must be applied squarely onto the fire to be effective. Any deviation from this will render it ineffectual.

Use of water as the extinguishing agent appears to be rather ineffective (even though the burning times observed have been increased) for polyethylene combustion. Again, the method of application is the critical factor involved. Under zero gravity conditions this may prevent water from being effective at all.

Figure 14 illustrates the combustion behavior of polyethylene in 100% oxygen atmospheres in the presence and absence of the CF_3Br extinguishant. Data for the other tests is too overlapping to permit the direct comparison to be made. These data should be compared with the zero gravity tests, discussed later in this portion of the report.

The effect of CF_3Br upon the Dacron Fabric combustion process is quite striking. All the tests conducted in 100% oxygen atmospheres showed from 33 to 70% increases in burning times. In diluent containing atmospheres the results were positive; the sample was not entirely consumed. Water as the extinguishing agent was generally ineffective. Use of protein foam produced good results. In 100% oxygen atmospheres at 256 and 386 mm Hg pressure, the tests were positive while the burning time in 569 mm Hg test was increased
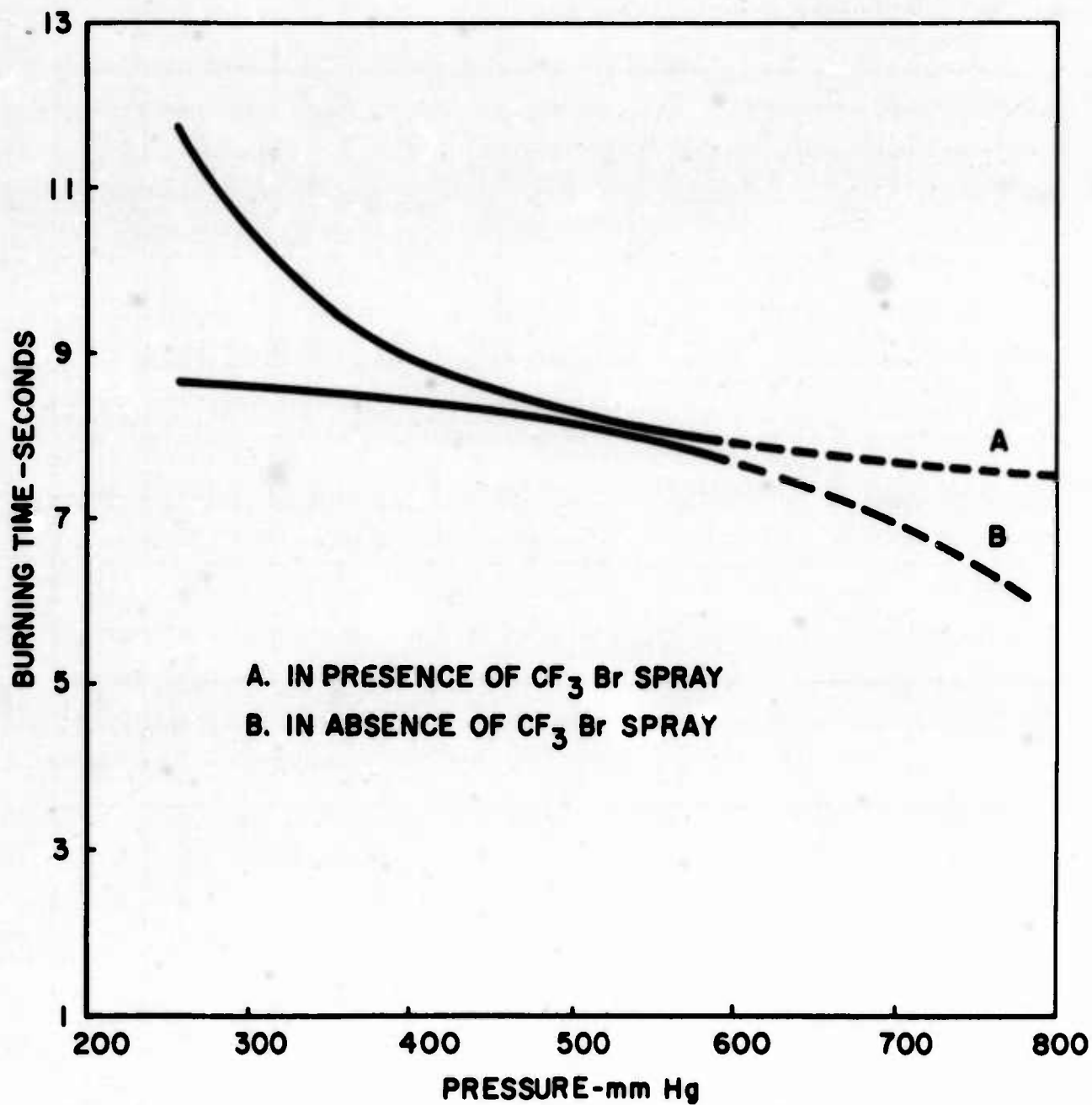
FIGURE 14. Combustion Behavior of Polyethylene in Initially 100% Oxygen Atmospheres at One Gravity:- Effect of CF$_3$Br Extinguishant.

by over 60%. Tests conducted in diluent containing atmospheres were positive. All the material was not consumed by the fire. Figure 15 illustrates the combustion behavior of Dacron Fabric in 100% oxygen atmospheres in the presence and absence of CF_3Br extinguishant. Comparison of the tests involving water and foam cannot be made in this manner because of the nature of the experimental results. As before, these data are to be directly compared to the zero test gravity data involving Dacron.

Use of CF_3Br as the extinguishant for mineral oil combustion in 100% oxygen atmospheres proved to be ineffective. In this case, the Freon appeared to increase the burning rate of the hydrocarbon, since the burning times decreased for each test. Large amounts of bromine were present at the end of each of these three tests. Only in the presence of helium, as the atmospheric diluent, did the Freon prove effective. Flame-out occurred in less than two seconds after application of the extinguishant. Water proved completely ineffective. Foam extinguishant succeeded in yielding positive results in 100% oxygen atmosphere at 569 mm Hg pressure, and in the atmosphere containing helium as the diluent. Figure 16 illustrates the burning time behavior of mineral oil in the presence and absence of CF_3Br extinguishant.

(b) Evaluation of Extinguishing Agents at One Gravity

Halon 1301 [CF_3Br] proved effectual in the majority of the experimental tests. If it did not actually extinguish the fire, it did reduce the burning rate, except in the 100% oxygen atmospheres-mineral oil fires. Quite possibly, increased concentration of the extinguishant would prove to yield positive results in all cases. The major advantages of this extinguishant are (1) its ease of application and (2) its relative effectiveness. The major disadvantages are (1) the liberation of toxic bromine and HBR during its application and (2) the corrosiveness of its degradation products.

Water is completely ineffectual.

Protein foam is effective, particularly in diluent containing atmospheres. The advantage of this agent is that it produces no apparent toxic degradation products. Its disadvantages are (1) it is effective only when in direct contact with the burning specimen (this implies a complicated application system),
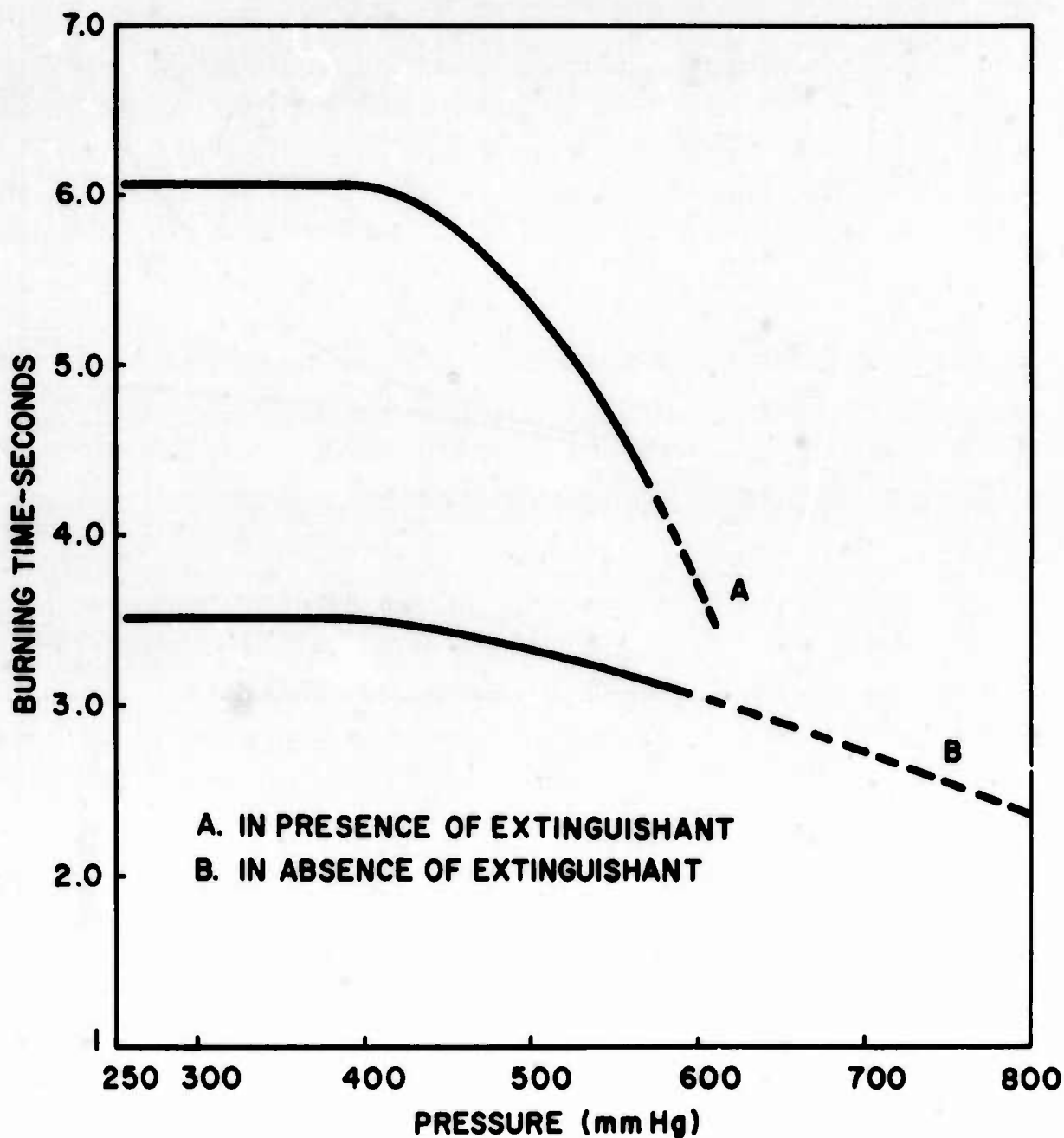
FIGURE 15. Combustion Behavior of Dacron Fabric in Initially 100% Oxygen Atmospheres at One Gravity:- Effect of CF_3Br Extinguishant.
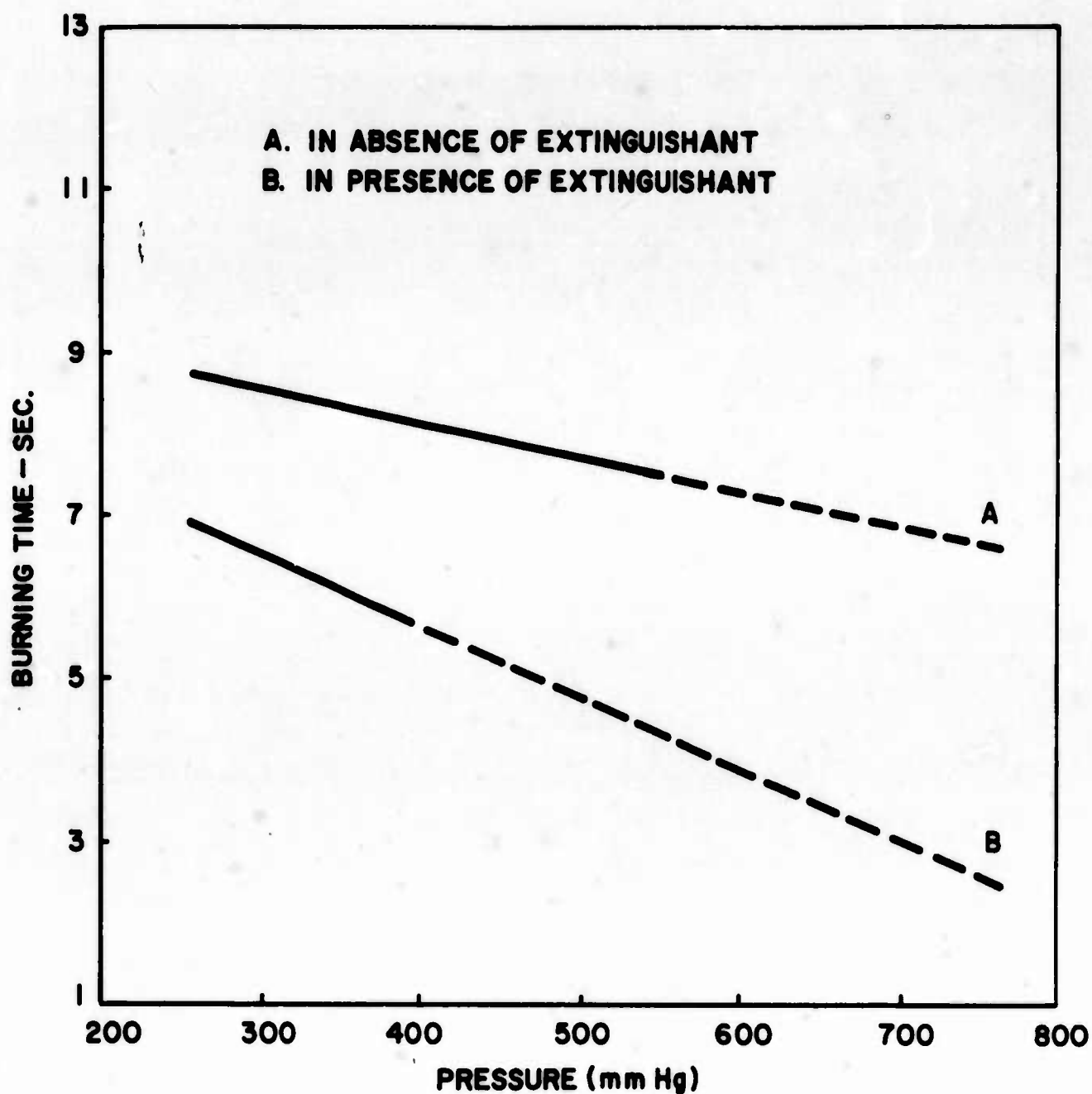
FIGURE 16. Combustion Behavior of Mineral Oil in Initially 100% Oxygen
Atmospheres at One Gravity:- Effect of CF_3Br Extinguishant.

and (2) it produces solid residual products which will require physical clean-up and removal from the area after the fire is extinguished.

(c) Burning Time at Zero Gravity in the Presence and Absence of Extinguishing Agents

The laboratory test program, discussed in the previous section, (a), supplied the norm with which the results of the zero gravity tests may be compared. All zero gravity tests were carried out within the NASA Zero Gravity Test Chambers, already described and illustrated by Figure 13. All the tests were recorded photographically, as was the one-gravity data, to facilitate comparison between them. For the zero gravity tests, the equipment was airborne and the test conducted within the few seconds of weightlessness available per flight.

Those tests involving the application of an extinguishant were conducted using Freon 13B1 as the extinguishing agent. In spite of the disadvantages noted for this agent, it still is the most attractive material tested. By using it in larger amounts it may be possible to quench the fire quicker and thereby prevent the extinguishant from undergoing excessive degradation. It is realized that under such application, the Freon is being used as a blanketing agent, hopefully, rather than as a chemical extinguishant. It is for this reason that CF_3Br was selected for tests at zero gravity conditions.

Twenty four tests were conducted under zero gravity conditions. Twelve were made using polyethylene test specimens. Twelve with cotton coverall material. In addition, six one gravity tests were made for comparative purposes using the cotton test samples. Time did not permit the scheduling and testing of other materials.

At the time this report was written, film records of only eight tests have been received and reduced. Table XIX presents these results. As noted, the tests include the variable of forced circulation, induced by fans placed within the test chamber. Comparison of the results obtained with and without forced circulation indicates that forced circulation has little, if any, affect upon the burning time under zero gravity conditions. The 20% variation so noted (between runs 4 and 7) may well be within experimental error; this error may be

TABLE XIX.   BURNING CHARACTERISTICS OF POLYETHYLENE AT ZERO
GRAVITY AS TESTED IN THE NASA ZERO GRAVITY CHAMBER
IN THE PRESENCE AND ABSENCE OF EXTINGUISHANT
SAMPLE DIMENSION: 2-1/4" x 1/8" x 1/16"

Run No.	Atm. Composition (%)			Pressure (mm Hg)	Extinguishant	Charge Pressure	Burning Time (Sec)	Remarks
	O₂	N₂	He					
1	100	--	--	569	--	--	14.5	No forced circulation.
2	100	--	--	569	--	--	20.0	No forced circulation
3	100	--	--	386	--	--	--	Faulty ignitor, no ign.
4	100	--	--	256	--	--	17.5	No forced circulation.
5	100	--	--	569	--	--	15.4	Forced circulation.
6	100	--	--	386	--	--	18.5	Forced circulation.
7	100	--	--	256	--	--	20.8	Forced circulation.
8	100	--	--	569	CF₃Br	75 psi	21.8	Forced circulation.

as much as 27% if the deviation between runs 1 and 2 are taken as the indicator of the error.

The effect of CF_3Br upon the zero gravity combustion process is not clear. If run 2 is correct, it has no significant effect. If run 1 is correct, it greatly retards the burning rate. Due to the scantiness of the data and the possibility of such a large experimental error, it is not practical to draw a firm conclusion at this time with regard to the effectiveness of CF_3Br as an extinguishant under zero gravity conditions.

The effect of zero gravity conditions upon the combustion process of polyethylene is effectively seen by comparing runs 1, 2, 4 and 6 of Table XIX, with runs 1, 2, and 3 of Table XVII. It is seen that the burning rate, under zero gravity, is reduced significantly. In view of this reduction, the effectiveness of the extinguishant should have been enhanced. That this did not take place is evident from the test results.

C. PHASE III. THE BURNING RATE OF MATERIALS AS A FUNCTION OF AMBIENT ATMOSPHERIC ENVIRONMENTS AND PRESSURES

1. Introduction

The experimental program reported upon in previous sections of this report, has shown that the ignition and combustion process of the test materials are, generally, a direct function of the oxygen concentration subject to the overall influence of the total ambient atmospheric composition. In this phase of the program, we investigated the combustion behavior of materials more closely. The objective, here, was to determine the effectiveness of selected closed environment-atmosphere gas compositions in moderating the combustion process. This was accomplished by noting the change in the flame spread rate, or burning rate, of the individual test samples as a function of the atmospheric environment and pressure. Since, in the tests reported below, the samples were consumed, the data is reported as burning rates rather than as flame spread rates. Air, at one atmosphere pressure, was selected as the normal atmospheric environment. All changes in the burning rates are noted relative to that observed in air for the test samples studied.

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Test materials studied in this phase of the work were drawn from those whose S.I.T. values have been ascertained in Phase I of the program. Two were also the subjects of the tests carried out in Phase II, as reported above. The tests were divided into two series. The first series were carried out in atmospheric environments containing oxygen, nitrogen or helium. The second series were carried out in atmospheres which included predetermined amounts of CF_3Br.

2. Experimental Apparatus

The combustion reactions were carried out within a reaction chamber which was, essentially, a seventy inch cube, made of 1/2 inch thick stainless steel. The front portion of the chamber was fitted with a removable ten inch square pyrex window, suitably gasketed, 3/4 inch thick, and held in place by a bolted framework. The system was capable of maintaining a vacuum of less than 3 microns of pressure, for 48 hours, isolated from the attached vacuum system.

At the rear of the chamber, provision was made for the insertion of ignition leads, exhaust, and atmosphere inlet lines. Pressure within the chamber was monitored by means of an absolute manometer and a pirani gauge. Both were attached to pressure ports located at the top center of the reaction chamber.

Samples to be tested were mounted onto a removable sample holder. This device consisted of two, 9-inch posts attached to a metal base, set 3 inches apart from each other. The posts were positioned at a 45-degree angle from the vertical. The samples were attached to the post holders by a clip arrangement. Dielectric terminal strips were attached to the base of each post and served to provide electrical connection between the ignition system and the electrical leads at the rear of the chamber.

Ignition was accomplished by means of a coiled nichrome wire heating element. Each element was one inch long and consisted of eight coils. The spiral diameter was approximately 1/4 inch. Each element had a 1/2 ohm resistance. Power, supplied to the heating element, was controlled by a variable transformer, and ranged from 32 to 77.4 watts, depending upon the

sample material under test.

3. Procedure

Physically, the samples were of one of two forms when received. Plastic materials were in the form of sheets. Fabrics were in the form of bolts. Each sheet, or bolt, was of a specified thickness. Individual test specimens were cut from the "as received" material. They consisted of 7 x 2-3/8 inch rectangles. To insure uniformity of the test specimens for a particular series of tests, each was weighed to within 0.1 gram. Only test specimens agreeing in weight to the nearest 0.1 gram were used. With the test samples mounted between the post holders, the combustible area was defined by a 7 x 1-7/8 inch rectangle.

Each specimen is marked one inch from the top and bottom edge when viewed lengthwise. The heating element is placed in contact with the lower edge. It is centered with respect to the sample width. The entire device is placed within the chamber, positioned at a predetermined site dictated by the photographic equipment requirements, located in front of the pyrex window of the chamber. The electrical leads are then connected, and the chamber window bolted into place.

The volume within the sealed chamber is evacuated by means of a mechanical pump system to a final pressure of 10 microns of mercury. A cryogenic trap is placed between the pump and the chamber, to (1) protect the operating personnel from any toxic vapor produced during the combustion process, and (2) to protect the pump. The chamber is isolated from the vacuum system and pressurized with the desired atmosphere up to the required operating pressure. At this point, a stopwatch is positioned at the lower right corner of the pyrex window.

The experimental test commences with the activation of the camera, followed by activation of the stopwatch. The stopwatch provides an auxilliary, independent time base for the test run. Activation of the heating element takes place 5 seconds after the stopwatch has been activated.

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Data sought in each test include the time to ignition, burning time to the one inch line, and the burning time to the six inch sample marker, as well as general burning characteristics of the test material. Energy requirements for ignition were established for each specimen in air atmospheres at atmospheric pressures. Energy requirements for ignition in other atmospheres and at other pressures were noted, these changes being an important characteristic of the test specimen.

4. Experimental Results in Absence of Extinguishant

(a) Burning Rate of Polyethylene

Burning rate data for this test material is presented in Table XX. This data is the result of 15 determinations made with polyethylene in atmospheres containing oxygen alone and in combination with nitrogen or helium. The first two runs, SN64-1 and SN64-2 were performed in air at atmospheric pressures in order to ascertain the ignition energy requirements of the system. This energy, noted as watt-seconds in the table, is the amount of energy that must be dissipated by the heating element in order to ignite the test specimen in contact with it. The above cited runs are noted as "standard runs" in the table, and the average energy calculated from them is termed the "standard energy." Energy requirements for other atmospheres and pressures are reported relative to this standard energy as "% of standard," as noted in column 7 of Table XX. This nomenclature, as defined, is used in conjunction with all the reported data in this phase of the work.

Analysis of the data indicates that there is approximately a 17 to 22% error inherent to the experimental method employed. This is evident from (1) the spread in the standard energy data reported, and (2) the spread in the observed burning rate data for tests conducted at 259 mm Hg pressure in 100% oxygen atmospheres. It is probable that the former error value is due to variations in the contact made between the heating element and the sample between the runs. The latter error value may arise from variations inherent with sample composition.

TABLE XX. BURNING RATE OF POLYETHYLENE IN VARIOUS AMBIENT ATMOSPHERES
AND AT VARIOUS PRESSURES IN ABSENCE OF EXTINGUISHANTS

Run No.	Atm. Composition (%) N₂	O₂	He	Pressure (mm Hg)	Time to Ignition	Variac Ignition Setting	Watt-Sec.	% of Standard	Time to 1" Line From Ignitor on - Sec.	Time to 6" Line (From 1" Line) - Sec.	Burning Rate- In/Sec	Remarks
SN-64-1	80	20	--	745	35	80	1120	100	--	--	--	Standard run
SN-64-2	80	20	--	745	30	80	960	100	--	--	--	Standard run
					Standard is 32.5 sec. @ 1040 watt-sec.							
SN-64-3	--	100	--	259	11.5	80	368	35.38	12.4	37.9	0.132	
SN-64-4	--	100	--	259	--	80	--	--	--	--	--	*
SN-64-5	--	100	--	259	8.5	80	272	26.15	19.2	31.0	0.161	Flame dripped
SN-64-6	--	100	--	259	--	80	Faulty Ignitor		--	--	--	
SN-64-7	--	100	--	259	11.9	80	380.8	36.62	23.5	39.6	0.126	Flame dripped
					Average ignition time: 10.6 sec.				Average burning rate:0.139			
					Average % standard: 32.71%							
SN-64-8	--	100	--	517	13.2	80	42.2	40.58	21.5	23.7	0.211	
SN-64-9	--	100	--	760	12.3	80	393.6	37.85	17.1	18.6	0.269	Sparks
SN-64-10	40	60	--	259	29.7	80	950.4	91.38	44.9	54.8	0.091	Flame dripped
SN-64-11	40	60	--	517	16.9	80	540.8	52.00	29.2	48.1	0.104	
SN-64-12	40	60	--	760	11.9	80	380.8	36.62	21.5	38.1	0.131	
SN-64-13	--	60	40	259	37.8	80	1209.6	116.3	46.8	50.5	0.099	
SN-64-14	--	60	40	517	20.8	80	665.6	64.0	25.1	39.1	0.128	
SN-64-15	--	60	40	760	14.1	80	451.2	43.38	21.5	23.9	0.209	

* No ignition, faulty ignitor.

The data given in Table XX clearly shows that:

1. The burning rate is directly proportional to the oxygen concentration.

2. The time to ignition is inversely proportional to the oxygen concentration, hence the energy required for ignition is also.

3. Burning rates in helium containing atmospheres are increased relative to those observed with nitrogen as the atmospheric diluent.

4. As the energy requirements for ignition decreases, the observed burning rates increase. The above relationship is observed in connection with other test material reported upon in this section of the report.

Figure 17 presents the observed relationship between the burning rate and oxygen concentration graphically. The data point for 100% oxygen atmospheres at 259 mm Hg pressure is represented by the average value of the three burning rate determinations conducted at this atmospheric environment.

(b) 7400 Dacron Fabric

Burning rate data for 7400 Dacron Fabric is presented in Table XXI. This data is the result of 15 experimental determinations carried out employing three ambient atmospheres at three different total pressures. Figure 18 graphically presents the burning rate data as a function of the oxygen concentration at the three total ambient environmental pressures employed. The atmospheres contained nitrogen as the diluent component where the oxygen concentrations are less than 100%.

For practical purposes, the data clearly shows the burning rate to be a linear function of the oxygen concentration. Further analysis of the tabulated data indicate that:

1. The time to ignition is inversely proportional to the oxygen concentration.

2. The energy requirements for ignition decrease as the oxygen concentration increases.
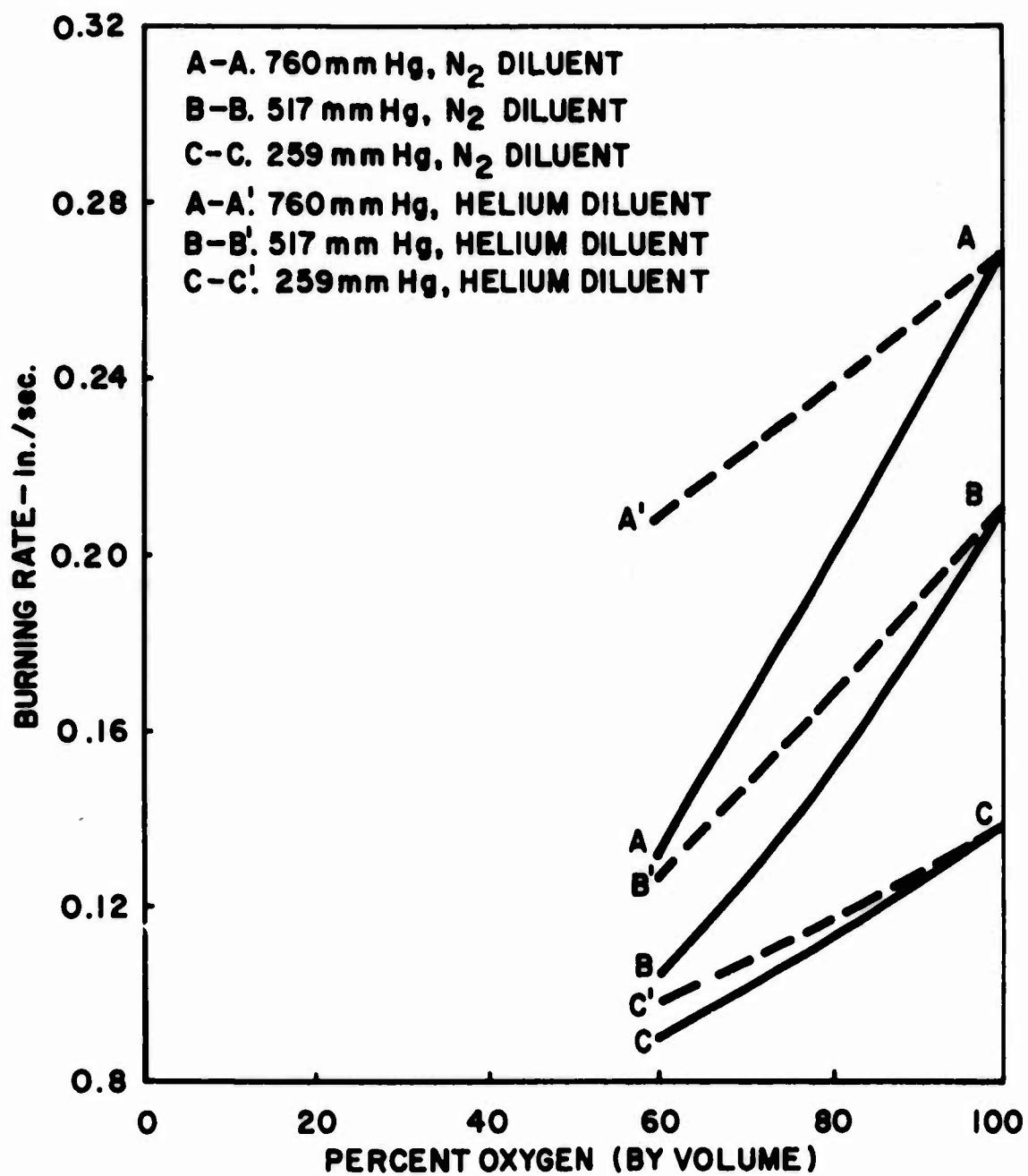
FIGURE 17. Burning Rate of Polyethylene as a Function of Oxygen
Concentration and Total Ambient Atmospheres.

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TABLE XXI. BURNING RATE OF 7400 DACRON FABRIC IN VARIOUS
AMBIENT ATMOSPHERES AND AT VARIOUS PRESSURES
IN ABSENCE OF EXTINGUISHANT

| Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time to Ignition Sec.	Watts	Watt-Sec.	% of Standard	Time to 1" Line From Igniter on - Sec.	Time to 6" Line (From 1" Line) - Sec.	Burning Rate- In/Sec.	Remarks
	O₂	N₂	He									
SN-64-16	20	80	--	740	10.2	44	448.8	--	6.9	11.8	0.423	Standard run
SN-64-17	20	80	--	740	10.8	44	475.2	--	6.3	11.9	0.420	Standard run
					Average watt sec = 462, taken as standard for this series.							
SN-64-18	100	--	--	259	8.5	44	374	80.91	1.2	3.8	1.31	Dripped flame
SN-64-19	100	--	--	259	9.0	44	396	85.71	1.2	3.5	1.42	
SN-64-20	100	--	--	517	8.5	44	374	80.91	0.72	3.3	1.51	
SN-64-21	100	--	--	760	7.5	44	330	71.43	2.3	2.2	2.27	
3N-64-26	60	--	40	259	4.6	72	331.2	71.68	1.5	5.8	0.862	
SN-64-24	60	--	40	517	4.0	72	288	62.33	1.5	3.2	1.56	
SN-64-25	60	--	40	760	4.7	72	338	73.15	0.66	4.2	1.19	
SN-64-27	60	40	--	259	9.6	44	422.4	91.42	1.3	6.3	0.79	
SN-64-28	60	40	--	517	10.2	44	448.8	97.14	1.2	4.4	1.14	
SN-64-29	60	40	--	760	9.3	44	409.2	88.57	1.1	3.7	1.35	Dripped flame
SN-64-30	20	80	--	740	10.6	44	466.4	--	5.1	10.5	0.476	Treat as standard
SN-64-31	20	80	--	517	14.2	44	624.8	135.2	6.7	12.0	0.416	
SN-64-32	20	80	--	259	18.3	44	805.2	174.3	9.7	16.4	0.305	Very smokey
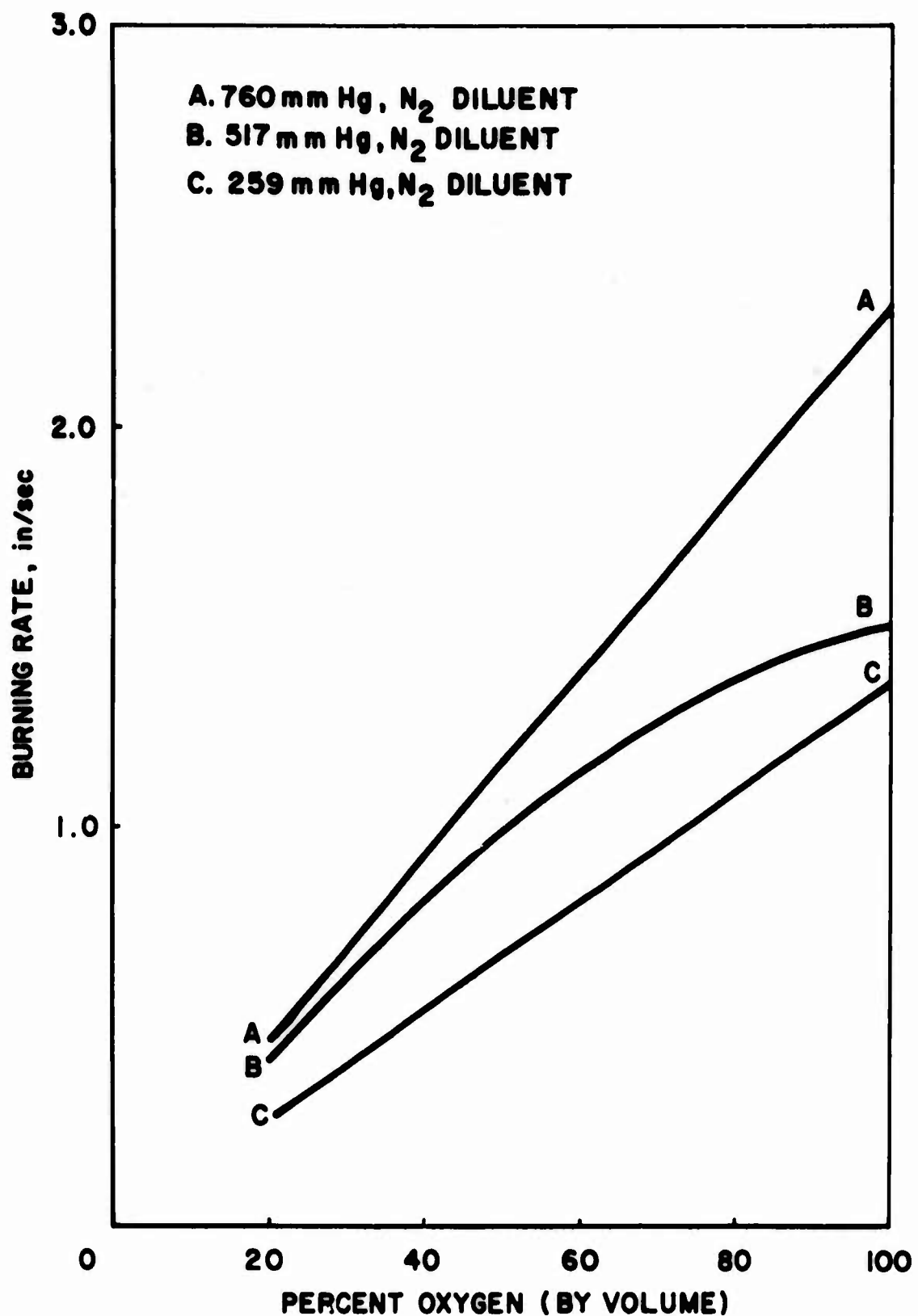
FIGURE 18. Burning Rate of 7400 Dacron Fabric as a Function of Oxygen
Concentration at Various Total Ambient Environmental Pressures.

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3. The burning rates in helium containing atmospheres are increased relative to those observed in nitrogen containing atmospheres at comparable pressures and oxygen concentrations.

It is felt that the deviations from the above cited trends, notably runs SN64-25 and SN64-28, are due to undiagnosed experimental errors. This very likely accounts for the low results obtained in run SN64-20, leading to the nonlinearity of curve B of Figure 18.

(c) MIL-C-7210 -- Type III Nylon Fabric

Table XXII presents the tabulated results for this series of tests. Figure 19 presents graphically the observed dependency of the burning rate upon the oxygen concentration, in nitrogen containing atmospheres, at various total environmental pressures. The three curves demonstrate that this dependence is virtually a linear function of the oxygen concentration at each experimental pressure employed.

Analysis of the data in Table XXII shows that:

1. The time to ignition is inversely proportional to the oxygen concentration.

2. The energy required for ignition decreases as the oxygen concentration increases.

3. The burning rate in helium containing atmospheres is increased relative to that observed in comparable nitrogen containing atmospheres under similar experimental operating conditions.

5. Experimental Results in Presence of CF_3Br Extinguishant

Two materials, polyethylene and cotton coverall fabric, were subjected to an intense study of their burning characteristics in the presence of CF_3Br. For this work, the CF_3Br extinguishant was utilized as an integral component of the ambient atmospheric environment. Cotton was not among those materials included in the previously reported experimental evaluations. It was studied here as a direct consequence of the Brooks Air Force Base fire which occurred while this program was in progress.

TABLE XXII. BURNING RATE OF MIL-C-7219, TYPE III NYLON FABRIC IN VARIOUS ATMOSPHERES AND AT VARIOUS PRESSURES IN ABSENCE OF EXTINGUISHANT

| Run No.	Atm. Composition (%)			Pressure (mm Hg)	Time to Ignition Sec.	Watts	Watt-Sec.	% of Standard	Time to 1" Line From Ignitor on - Sec.	Time to 6" Line (From 1" Line) - Sec.	Burning Rate- In/Sec.	Remarks
	O₂	N₂	He									
SN-64-33	20	80	--	740	7.4	72	532.8	--	7.4	6.5	0.173	*
SN-64-34	20	80	--	740	6.1	72	444.2	--	11.1	32.4	0.154	Flame drippe
SN-64-46	20	80	--	740	7.0	72	504	--	5.0	30.0	0.166	
					Average watt sec. = 493.6, take as standard value.							
SN-64-35	100	--	--	760	5.4	72	388.2	78.65	1.6	4.9	1.02	
SN-64-36	100	--	--	517	5.7	72	410.4	83.64	1.7	5.6	0.89	
SN-64-37	100	--	--	155	8.0	72	576	116.5	3.4	10.7	0.47	
SN-64-38	100	--	--	259	7.4	72	532.8	100.0	2.1	6.7	0.75	Drip flame
SN-64-39	60	40	--	760	7.0	72	504	102.1	2.3	7.8	0.64	Drip flame
SN-64-40	40	60	--	517	8.0	72	576	116.5	2.9	13.9	0.36	Drip flame
SN-64-41	60	40	--	517	6.1	72	444.2	90.0	2.8	9.7	0.51	
SN-64-42	60	40	--	259	7.6	72	547.2	110.9	2.5	11.2	0.45	Drip flame
SN-64-43	60	--	40	760	7.0	72	504	102.1	--	6.0	1.00	
SN-64-44	60	--	40	517	8.0	72	576	116.5	--	8.0	0.75	
SN-64-45	60	--	40	259	8.0	72	576	116.5	--	10.0	0.60	
SN-64-47	20	80	--	517	8.0	72	576	116.5	7.0	40.0	0.125	
SN-64-49	20	80	--	259	--	--	--	--	--	--	---	No ignition

* Flame out 1-1/8" over base.
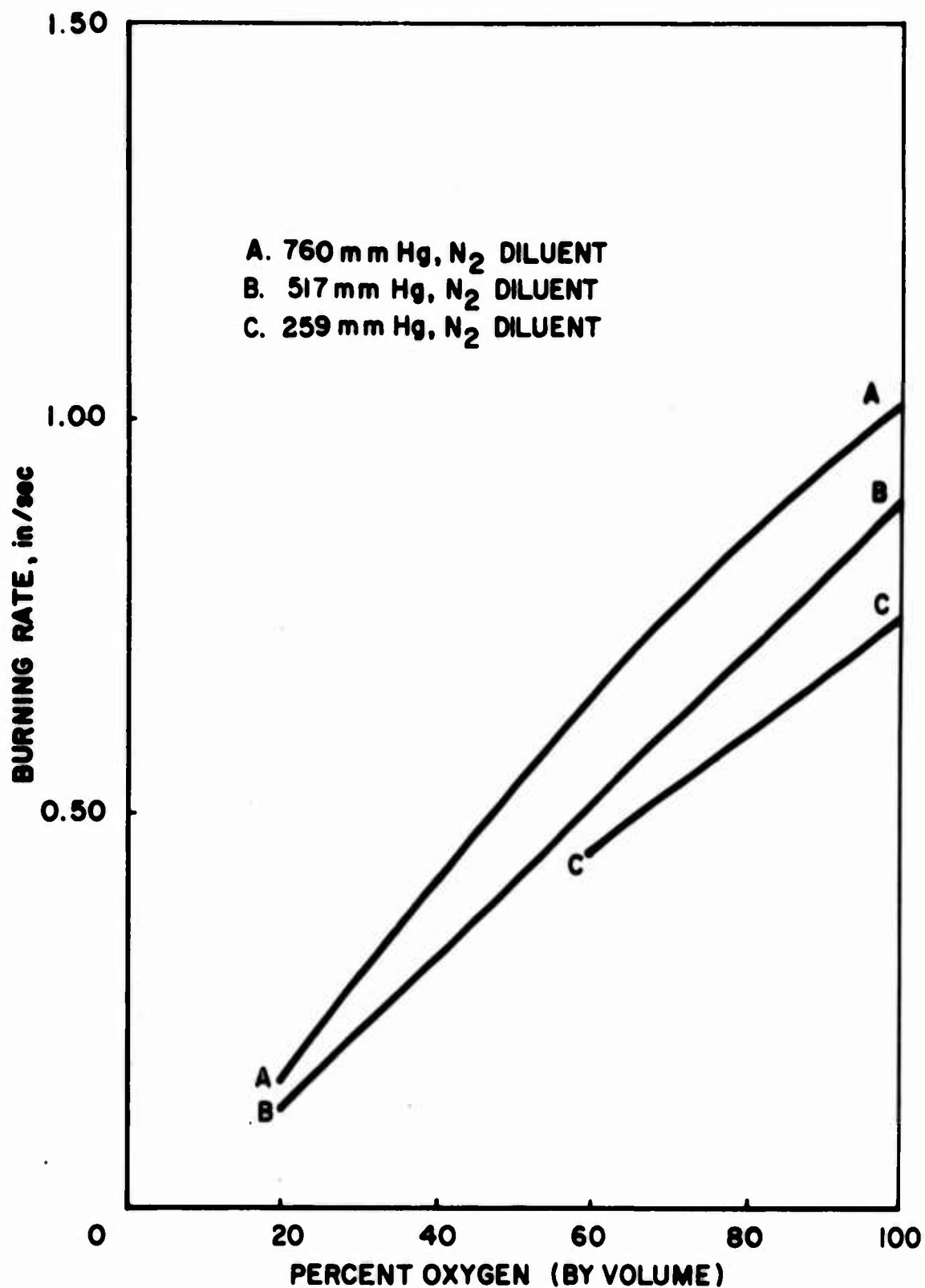
FIGURE 19. Burning Rate of MIL-C-7219--Type III Nylon Fabric as a Function of Oxygen Concentration at Various Total Ambient Environmental Pressures.

A total of twenty four experimental tests were conducted, nine with polyethylene and fifteen with cotton fabric. Spot checks were also made employing Nylon, Dacron, and Orlon fabrics as test specimens. Each experimental run was filmed. Unfortunately, time did not permit the complete reduction of all of the filmed data. Only the data of nine runs were reduced; four using cotton fabric specimens and five employing polyethylene specimens. These data are presented in Tables XXIII and XXIV respectively. Results, based upon the visual observations of the individual experimental tests are presented by Figure 20.

The observed data are classified according to the following scheme. In the event the test specimen did not ignite at all, the results are termed positive. When the sample ignited and burned, the result is termed negative. In the case where ignition occurred, but the subsequent flame was extinguished, the result is termed intermediate.

Where ignition did occur, the ignition characteristics of the system differed sharply from those previously cited in Section C-4 of this report. First, the power required to achieve ignition was generally higher than that employed for the tests conducted in the absence of CF_3Br. Secondly, charring and glowing (smoldering) characterized the ignition and "burning" process in the majority of positive and intermediate results as defined above. Where a flame did appear, it would be after the sample smoldered. It was impossible to ascertain the actual time to ignition visually, hence the energy required for ignition could not be deduced from the visual data. In the case of intermediate results, burning was generally restricted to the vicinity of the sample up to, or below, the one inch marker.

Figure 20 presents the results of this series of tests, as a function of the CF_3Br/O_2 pressure ratio, at given total ambient pressures. All atmospheric environments utilized for these tests were restricted to oxygen and CF_3Br. The data falls within three general areas, the ignition zone, transition zone, and the no ignition zone. Here the transition zone represents the intermediate results noted above; the other two -- the negative and positive respectively. Included are the data for Orlon, Nylon, and Dacron.

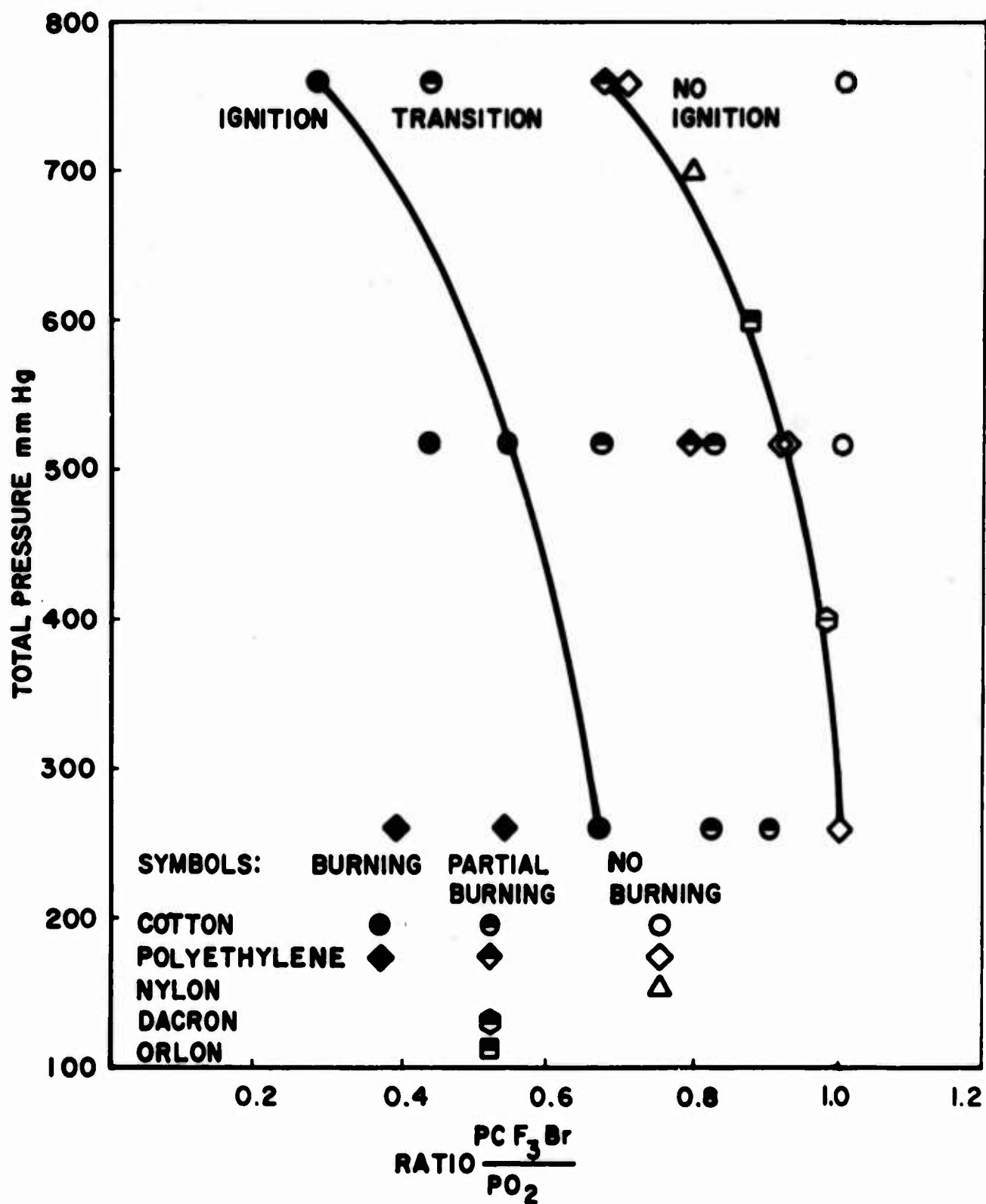The initial runs were made with polyethylene and cotton, as test samples.

FIGURE 20. Ignition and Burning Characteristics of Materials in the
Presence of CF_3Br-Oxygen Atmospheres at Various Total
Ambient Environmental Pressures.

It became obvious that a pattern was emerging which showed:

1. A region of low CF_3Br concentrations within which the sample would ignite and burn.

2. A region of intermediate CF_3Br concentrations within which the sample would ignite, burn, followed by extinction of the combustion process.

3. A region of CF_3Br concentrations within which the sample would not ignite.

These regions are readily discernable in Figure 20. The curves drawn define the apparent boundaries of these regions, which are to a first approximation independent of sample type. To check this, runs were made using Orlon, Nylon, and Dacron. CF_3Br concentrations just within those defined for the "No Ignition Region" were used. As is shown, Nylon did not ignite. Dacron and Orlon did ignite, but the combustion process was extinguished as soon as the material burned away from the vicinity of the heating element, thus generally verifying the boundary regions shown.

The tabulated data, Tables XXIII and XXIV, indicate the dependency of the ignition process upon both the actual oxygen concentration and the CF_3Br/O_2 ratio present. In the case of cotton fabric, flames appear only when the total pressure is relatively high even when the CF_3Br/O_2 ratio equal unity. This phenomenon definitely supports the general shape of the curves shown in Figure 20. It is noted, that for each of these cases, the flame was extinguished as soon as the cloth burned away from the ignitor.

Similar effects are noted with regard to the polyethylene tests, Table XXIV. In addition, the effect of changing CF_3Br/O_2 ratios to values < 1 are noted. Here, regardless of the total pressure, as the ratio decreases the system ignites more readily and the ensuing flame persists longer.

TABLE XXIII. BURNING RATE OF COTTON FABRIC IN ATMOSPHERES CONTAINING CF$_3$Br and O$_2$ AT VARIOUS PRESSURES AND RATIOS

Run No. SN-64	Atm % O$_2$	CF$_3$Br	Pressure mm Hg.	Time to Ign. (sec)	Variac Setting	Watts	Watts-Sec.	Time to 6" Line (sec)	Burning Rate Inch/sec	Remarks
65	50	50	260	10.1	125	77.35	781.2	-	-	Glow–10.1 sec. No flame anytime
69	52.51	47.49	259	7.53	125	77.35	582.4	-	-	Flow in vicinity of ignitor only
70	50	50	516	7.0	125	77.35	541.5	-	-	Small flame in vicinity of ignitor. Flare up due to burn out of ignitor. Much smoke Flame out when ignitor is out.
71	52.42	47.58	517	8.4	125	77.35	649.7	-	-	Flame in vicinity of ignitor only. Ignitor burned out. Much smoke. Flame out when ignitor is no longer operative.

TABLE XXIV. BURNING RATE OF POLYETHYLENE IN ATMOSPHERES CONTAINING CF_3Br and O_2 AT VARIOUS PRESSURES AND RATIOS

Run No. SN-64	Atm % O_2	CF_3Br	Pressure mm Hg.	Time to Ign. (sec)	Variac Setting	Watts	Watts-Sec.	Time to 6" Line (sec)	Burning Rate Inch/sec	Remarks
64	64.48	35.52	259	12.5	125	77.35	966.8	105.75	0.0321	Multiple vapor flash-overs. Time to ign. taken as time to first vapor flash-over
81	52.03	47.97	517	9.33	125	77.35	721.7	-	-	Flame in vicinity of ignitor only. Ignitor burn through specimen flame-out. No vapor flash over.
82	50	50	260	8	125	77.35	618.8	-	-	Flame in vicinity of ignitor only. No flame above 1" line. Flame out when ignitor burns through specimen.
83	52.41	47.59	517	10.1	125	77.35	781.2	-	-	Flame in vicinity of ignitor only. Flame out when ignitor off.
84	60	40	760	7.79	125	77.35	602.6	-	-	Fire extended over 1" line by a hair. Flame extinguished, then reignites on further application of heat to specimen.

III. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are evident, based upon the experimental results detailed in the body of this report.

1. The flammability and ignition behavior of materials of specified geometric shapes are defineable in terms of five measurable characteristics, namely,

    a. time to ignition
    b. energy required for ignition
    c. spontaneous ignition temperature
    d. burning time
    e. burning rate

2. Each of the above characteristics are dependent upon the oxygen concentration of the ambient atmosphere, when employing a specified amount of material. This dependency is expressible as:

    a. Burning rate is directly proportional to the oxygen concentration.

    b. Items a through d, in 1 above, are inversely proportional to the oxygen concentration.

3. Diluents, present in ambient atmospheres containing a specified oxygen concentration, have the affect of altering the observed values of the five characteristics noted above. They will not change the order of the observed values relative to varying oxygen concentration, i.e., diluent containing atmospheres with high concentrations of oxygen will yield faster burning rates than those with lower oxygen concentrations, etc., for specified materials.

4. CF_3Br, employed in large concentrations, is an effective extinguishant. At high CF_3Br/O_2 ratios, little or no bromine is liberated indicating it behaves as a blanketing agent under such circumstances. At lower CF_3Br/O_2 ratio, CF_3Br presents a hazard

as well as being of questionable value. Under these conditions it will retard, but not stop the existing fire. At the same time, varying amounts of Br_2, and possibly other toxic, corrosive, products are formed. At low CF_3Br/O_2 ratios, it appears that CF_3Br acts as a chemical agent and is of doubtful merit.

5. The burning process is affected by the reduction of gravity. At "zero gravity" conditions, the burning process of specified materials is retarded by as much as 50% relative to that taking place at one-gravity, under similar environmental conditions. The effectiveness of CF_3Br at zero gravity, as an extinguishant, has not been verified based upon the observed results of such tests.

The relationships shown to exist among the five characteristics of the ignition and combustion process, as well as between them and the oxygen concentration, clearly indicate that it should be possible to parametrically evaluate them. To do so requires that the material geometry be defined or that the affect of geometry upon the material ignition and combustion be known. Also required are data pertinent to one or more of the ignition characteristics of a given material.

It is, therefore, recommended that:

1. A mathematical program be initiated which will lead to the formulation of the necessary parametric equation or equations.

2. The current experimental program be continued, extending the present study of the ignition and combustion process to include the effects of material geometry. The experimental data would also make available the values of S.I.T. and ignition energy requirements needed for the parametric study.

3. A continuing study of materials as applied to space flight vehicle cabins be in progress. This could be done in conjunction with recommendation 2, above.

4. The search for an effective extinguishant be continued. Specifically, agents that will not yield toxic products should be sought and evaluated.

REFERENCES

1. Operating Manual, Dynamic Science Combustion Monitor Model 164, Dynamic Science, 1963.

2. Fisher, H. D., Gerstein, M., "Investigation of Materials Combustibility and Fire and Explosion Suppression in a Variety of Atmospheres," Summary Report SN-6401, Contract AF 33(615)-2257, Dynamic Science, 1966.

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13. ABSTRACT

Combustibility studies of materials of construction employed in space flight vehicle cabins have been carried out as a function of various simulated cabin atmospheric environments. The program was conducted under three distinct phases. Phase I efforts were directed at defining the spontaneous ignition temperature, of the individual materials, under dynamic atmospheric conditions for the various atmospheres employed. Phase II centered about the burning characteristics of the respective materials as a function of atmospheric and gravitational environments. These studies also involve the effects of various extinguishants upon the burning characteristics under the influence of several atmospheric environments and gravitational variations. Phase III focused upon the flame spread behavior of the material, under the influence of various atmospheric environments and in the presence of Halon 1301 flame extinguishant. Detailed analyses of the work clearly show the dependency of the combustion behavior of the materials upon the atmospheric environment utilized.

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